



FIBER OPTICS

FROM AMERICAN OPTICAL COMPANY

- FIBERSCOPES
- FLEXIBLE LIGHT GUIDES
- IMAGE CONDUIT
- CLAD RODS
- ILLUMINATORS



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Optical Hole Sensing Using Fiber Optics

William L. Stahl and Robert J. Potter

An important application of fiber optics to data processing is to illuminate hole positions of punched-card reading-stations. In the IBM 59 Card Verifier, flexible incoherently oriented bundles are employed to provide a reliable, efficient, and practical method of sensing holes in punched cards. A phototransistor detects the light coming through open holes and then operates a reed relay directly. In addition, a mechanical light chopper also uses fiber optical components to provide light pulses for the electronic clock to time the machine. An electronic circuit is used to latch reed relays so that the useful signal is digital, rather than the analog hole-to-no-hole light ratio.

Introduction

Optical fiber bundles are being used in the optical system of the IBM 59 Card Verifier to sense holes in punched data cards. As far as we know, this is believed to be the first, large-quantity application of fiber optics.

Flexible glass fiber bundles with incoherent orientation (nonimage forming) are used in this machine to distribute light from a single lamp to twenty-six phototransistors. Twelve of these sensing elements are used to scan cards at each of two reading stations. The data is, of course, in the form of holes punched in the cards. The two additional photosensors are actuated by a train of light pulses from a mechanical shutter that provides timing for the machine operation. The output current of the phototransistors is used directly, without amplification, to operate relays of the type employing reed switches.

The use of fiber optics, phototransistors, and reed relays in a compatible system makes a card-reading machine much quieter, faster in automatic function, and easier to maintain.

Optical System

Three separate, fiber bundle assemblies are used. One is used for each of two card-reading stations.

of these channels is directed at one of the hole positions on an IBM card. A schematic drawing of the optical system is shown in Fig. 1. These twelve smaller bundles are positioned by a molded part. Appropriate grooves are provided in the molded part, and a suitable quantity of fibers is placed in each groove and held in place by epoxy. Figures 2 and 3 are photographs of one of these assemblies.

The material from which the moldings are made is a glass-filled phenolic that exhibits wear characteristics similar to those of the glass fibers. This permits uniform resistance to abrasion by the passing cards. With this arrangement, there are no cracks or crevasses in the area, in which accumulated card dust or foreign material can be harmful to the operation of the device.

The optical fibers are between $20\ \mu$ and $50\ \mu$ in diam. They are bundled in flexible, plastic-covered metal tubing and divided into groups such that the individual reading positions are illuminated by bundles 0.9 mm in diam. The light emerging from each of the twenty-four pipes located at the two scanning stations is shown through an air gap of approximately 0.3 mm upon the surface of a clad rod 1.27 mm in diam. It is through this gap that the scanned card is passed.

The individual fibers and the clad rods are made of core glass with an index of refraction of 1.62 and cladding of index of refraction of 1.52, resulting in a me-

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OPTICAL FIBERS are constructed of a glass core surrounded by a glass cladding of a lower index of refraction and transmit light by the phenomenon of total internal reflection. Rays entering one end of the fiber are carried by multiple internal reflections to the opposite end. A bundle of randomly arranged fibers will transmit light only. A

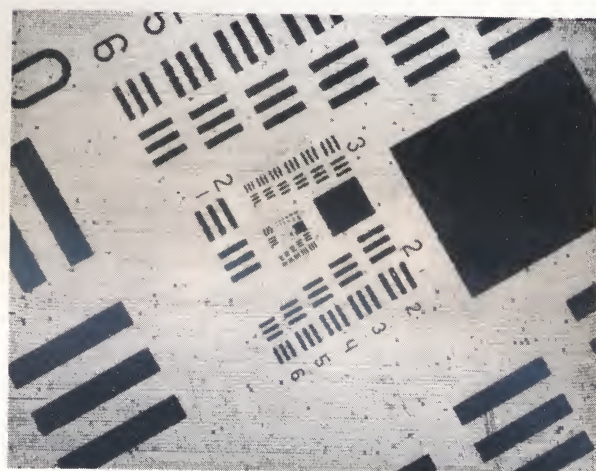
"coherent" fiber bundle, i.e. one in which both ends are arranged in an identical pattern, will transmit an optical image by breaking it up into thousands of separate components, one for each fiber, and conducting them independently from one end of the bundle to the other.

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A flexible Fiberscope consists of a "coherent" fiber bundle containing thousands of optical fibers cemented only at the ends and free to flex in between. To obtain both high image resolution and freedom from distortion, American Optical Company utilizes "multifibers" in the construction of its Fiberscopes. Multifibers consist of a number of optically distinct coated fibers fused into a single strand. They have essentially the same mechanical properties as single fibers of the same dimensions. Standard multifibers consist of a square array of 36 fiber elements, each 10 microns in diameter.

The photograph at the right shows the image of a standard resolving power target transmitted through a 6-foot long FS-162 Fiberscope. It illustrates the typical resolution of 45 line pairs/mm for standard AO Fiberscopes.

Fiberscopes can be used to inspect hard-to-reach



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ALLIED RADIO

111 North Campbell Ave.

Chicago 80, Illinois

EDMUNDS SCIENTIFIC

101 E. Gloucester Pike

Barrington, New Jersey

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The use of fiber optics, phototransistors, and reed relays in a compatible system makes a card-reading machine much quieter, faster in automatic function, and easier to maintain.

Optical System

Three separate, fiber bundle assemblies are used. One is used for each of two card-reading stations. The third which is used to synchronize the machine is described later. Each of the first two assemblies feeds light to a twelve-channel reading station. Each

of these channels is directed at one of the hole positions on an IBM card. A schematic drawing of the optical system is shown in Fig. 1. These twelve smaller bundles are positioned by a molded part. Appropriate grooves are provided in the molded part, and a suitable quantity of fibers is placed in each groove and held in place by epoxy. Figures 2 and 3 are photographs of one of these assemblies.

The material from which the moldings are made is a glass-filled phenolic that exhibits wear characteristics similar to those of the glass fibers. This permits uniform resistance to abrasion by the passing cards. With this arrangement, there are no cracks or crevasses in the area, in which accumulated card dust or foreign material can be harmful to the operation of the device.

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The individual fibers and the clad rods are made of core glass with an index of refraction of 1.62 and cladding of index of refraction of 1.52, resulting in a meridional numerical aperture of 0.56. Consequently, the light from both fiber bundles and rods emerges with approximately a 30° half-angle of divergence. Thus, essentially all of the light emerging from each bundle is incident upon the associated and slightly larger clad rod unless, of course, the light is cut off by the presence of a card that is not punched in the position being scanned.

The light from the far end of the clad rod shines upon a lens with a diameter of 1.524 mm, which, again,

W. L. Stahl is with IBM Corporation, Systems Development Laboratory, Kingston, New York. R. J. Potter was with IBM Corporation, Thomas J. Watson Research Center, Yorktown Heights, New York, when this work was done; he is now with Xerox Corporation, Research Division, Rochester, New York.

Received 8 December 1965.

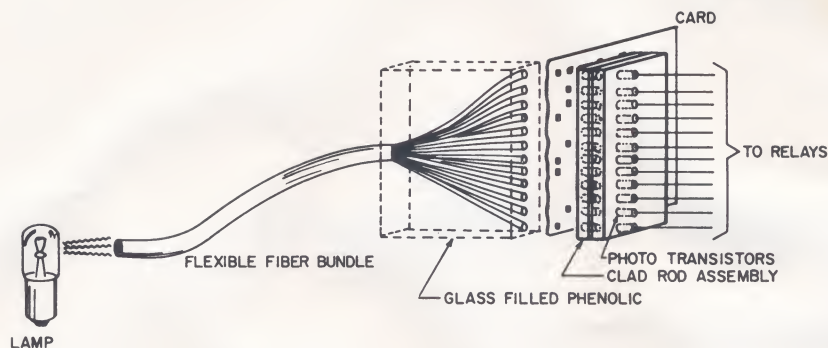


Fig. 1. Optical system of IBM 59 Card Verifier.



Fig. 2. Fiber optic bundle assembly—epoxy side.

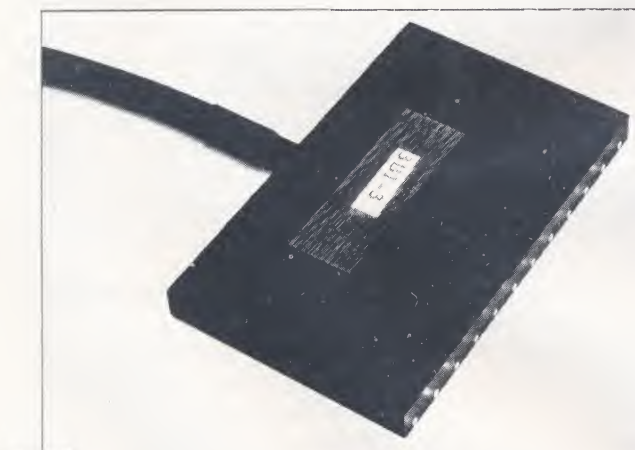


Fig. 3. Fiber optic assembly—molded side.

is larger than the rod and forms the surface of the phototransistor assembly. The light is then focused upon the light-sensitive chip within the sensing ele-

ment. Two different clad-rod assemblies are shown in Fig. 4.

The fiber optic assemblies are required to exhibit a minimum transmission of 35%. Specifications have been set for the capability of the fiber bundles to retain transmission efficiency after subsection to a program of bending and vibration.

Figure 5 contains photographs that show views of the ends of flexible bundles, one of which has been significantly damaged. The effect of such damage on light-transmitting characteristics is clearly evident.

The entire machine has been subjected to atmospheric shock tests. Temperature has been abruptly raised and lowered to values well in excess of any normally expected condition. No harmful effect has been observed for either the fiber bundles or any other portions of the machine.

The use of flexible fiber bundles allows the lamp to be mounted in a location that is effectively vibration-free, virtually eliminating the most frequent cause of premature lamp failure. Because of the efficiency of the optical system, the life of the lamp is prolonged further by operating it at approximately one-half of its rated voltage. Thus, a lamp with a life rating of 25 h can be reasonably expected to operate for as long as 50,000 h (see Fig. 6).

Comparison of the current-carrying ability of the phototransistors with the current required to operate the reed relays under consideration indicated that it would be practical to operate the relays directly from the current passed by the photosensors. This conclusion was verified experimentally.

It was necessary, however, to illuminate the phototransistor at the relatively high light level of 150 mW/cm² in order to guarantee satisfactory relay operation. Obtaining this level of illumination without excessive heat in the narrow physical confines dictated by the transistor dimensions might have been a problem. However, the use of fiber optics helped greatly in providing a solution to this problem by conducting light to the phototransistors without attendant heat transmission. By this means it was also possible to deliver the required light level from a source of suitable



Fig. 4. Two types of clad rod assemblies.

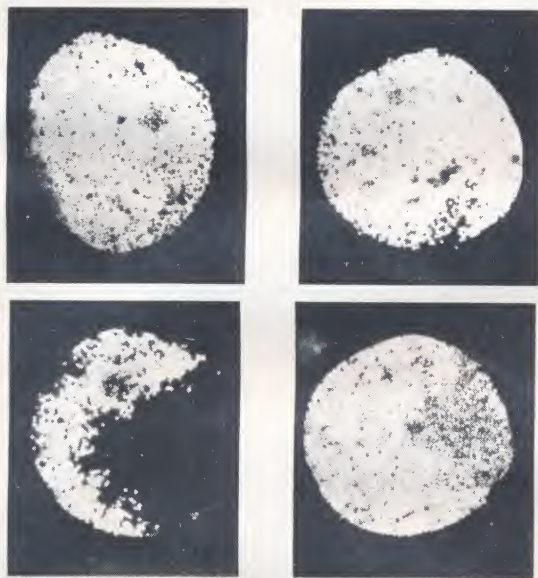


Fig. 5. Microphotographs of ends flexible bundles.

dimensions. Another advantage of this design, therefore, is the enhancement of the stability and life expectancy of the photosensors.

Electronic System

A card is somewhat translucent. The hole-to-no-hole light ratio has been measured and found to be approximately 8:1. This ratio is enough to guarantee that a relay will be energized only when a hole is sensed.

However, a relay, once it is energized, can be held in that state with considerably less current than that required to energize it initially. The current due to translucency of the card might be sufficient to con-

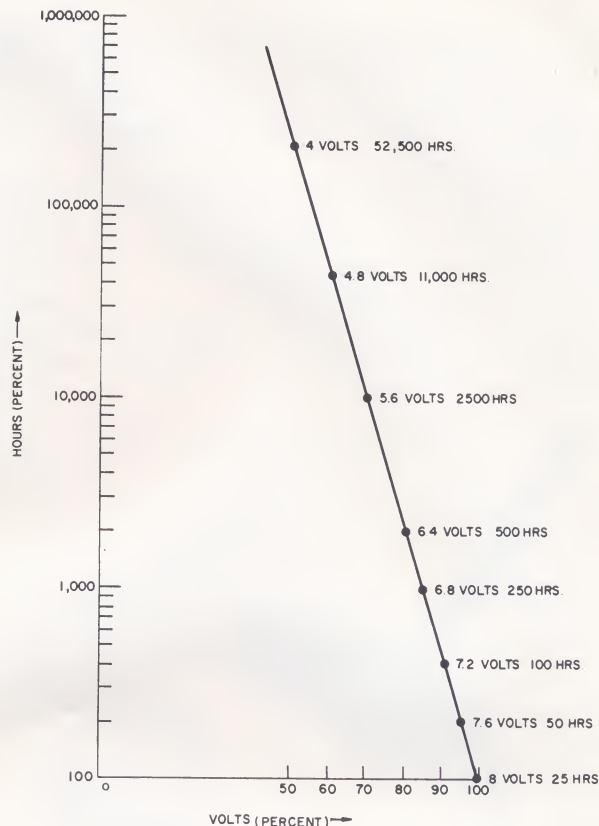


Fig. 6. Lamp light vs voltage.

tinue to hold the relay in the energized state. Because of this circumstance, a relay that is activated by the positioning of a hole at the sensing point might not be released when the hole has been moved away. In order to avoid this condition, the light intensity would have to be reduced.

The conflicting requirements of having a sufficiently high light level to operate a relay when a hole is sensed and a sufficiently low intensity to guarantee de-energization of the relay when the hole had passed would severely limit the operable light range. This possible restriction in the operable light range is completely removed by the use of the *photoemitter*, which is a mechanical chopper providing light pulses to control and synchronize the machine operation.

The emitter is composed of a totally opaque drum that is appropriately slotted to interrupt light from the third fiber bundle. This bundle is bisected so that each half operates a separate phototransistor. Figure 7 is a photograph of one of these fiber optic assemblies. The output of one phototransistor is used for timing between cards. The output of the other transistor develops a pulse synchronized with each card column.

These eighty pulses operate a relay used to de-energize—before the next column is sensed—any of the twenty-four sensing relays that may have been energized through holes in any given card column. This circuit arrangement is shown in simplified form in Fig. 8.

Thus, the total opacity of the light chopper is substituted for the considerably less-than-total opacity of the card stock as the determining factor in de-energizing the relays operated by means of holes punched in the card.

As a further improvement in the operable, light-intensity range, one circuit of each of the sensing relays is used to hold itself closed, instead of depending on only the light intensity to do so.

The reed relays used in this machine are specified to operate in less than one msec. At eighty columns/sec, the highest operating speed, each column is scanned in 12 msec.

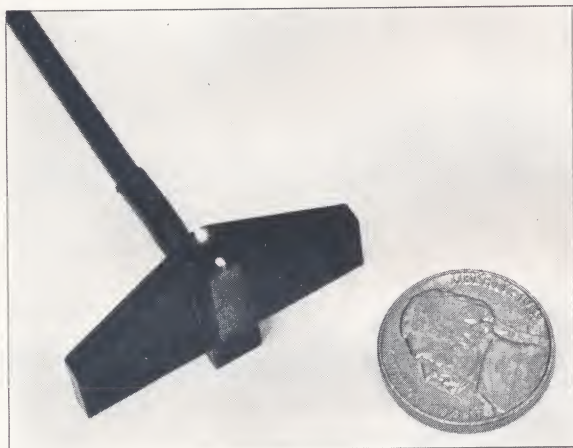


Fig. 7. Fiber optic assembly of emitter.

Summary

The application of fiber optics to the described data processing is believed to be the first large-scale, commercial use of optical fiber bundles. The technical

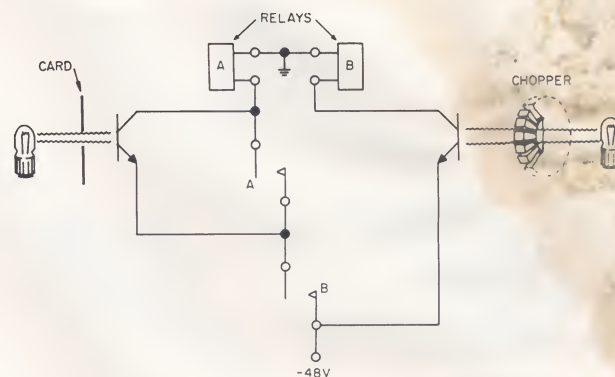


Fig. 8. Simplified scanning circuit.

literature has been used to describe many possible applications of fiber optics, several of which are quite sophisticated. In this case, the fiber optics is simple and became commercially practical for a number of reasons: (1) the flexible bundles allow mechanical isolation of the lamp; (2) the optical sensing reduces the mechanical requirements of the machine; (3) the transmission and durability of the fiber optics is adequate for the system's needs; (4) the advent of suitable phototransistors and reed relays allows an operation where the fiber optics deliver enough light to the phototransistor to provide sufficient current to activate the reed relay without the need of intervening electronic circuits; (5) the fiber bundles transmit high intensity light without transmitting heat; (6) the fiber optics makes possible a convenient, economical, small-sized source of high intensity light; (7) the fiber optics makes it practical to use one light source for the entire operation instead of a multiplicity of light sources.



photo Mitchell Valentine

E. J. W. Moore IBM (left), D. Z. Robinson Office of Science and Technology, D. J. Lovell Michigan, and D. Marquis P.A.A.

FIBER OPTICS: PRINCIPLES, PROPERTIES and DESIGN CONSIDERATIONS

by

Walter P. Siegmund

American Optical Company

Southbridge, Massachusetts

U. S. A.

ABSTRACT

The basic principles of fiber optics are reviewed and the properties of a variety of fiber optics materials are described. Important design considerations are discussed with respect to the application of these materials to various optical problems. To illustrate these design considerations a number of specific optical problems and their possible solution by means of fiber optics are described.

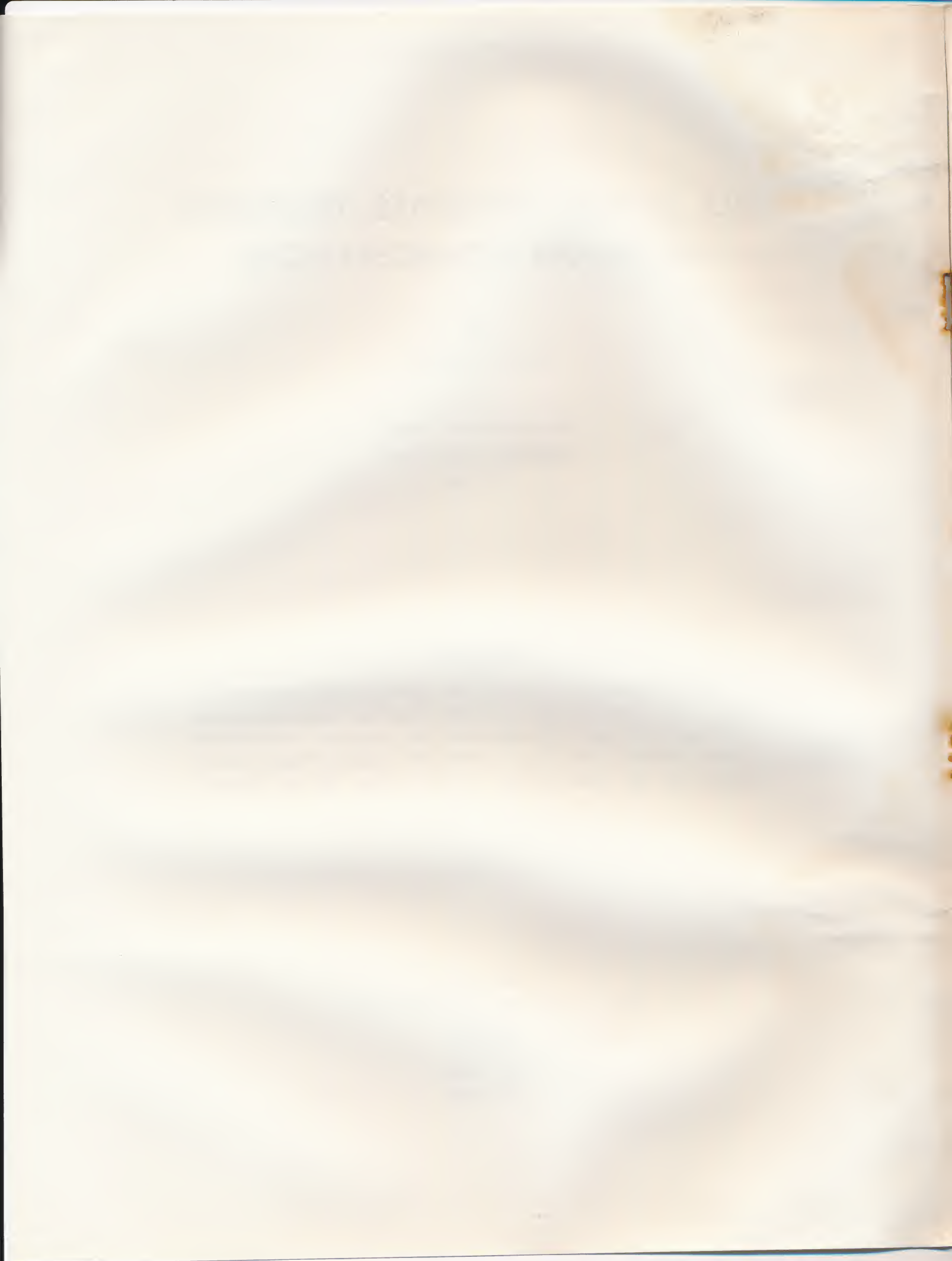
Presented at

6th Annual Meeting of the Avionics Panel

AGARD
(NATO)

Paris, France

July 1962



Historical

It has long been known that a smooth transparent cylinder such as a glass rod is capable of transmitting light by multiple internal reflections along its walls. It is not recorded who first observed that this phenomenon also occurs when the rod is of very small diameter i.e. in a filament or fiber, but an early paper by Schriever¹ describes some experiments on dielectric waveguides.

The possibility of conducting images by means of a bundle of fibers was first proposed in patents filed by Baird² in England in 1926 and Hansell³ in the U.S. in 1927. This concept was apparently first reduced to practice by Lamm⁴ in Germany in 1930, therefore giving the origin of fiber optics a decidedly international flavor.

During the next two decades a number of patents were filed on a variety of applications for fiber optics but little is recorded concerning their reduction to practice. From what is now known regarding the importance of optical insulation, i.e. coated fibers, it would not be surprising if all or most of these inventions may have failed in practice.

Not until the early 1950's when van Heel in the Netherlands and O'Brien in the U.S. began investigating the problem of optical insulation did fiber optics finally emerge as a practical technology. Van Heel first published his results in 1953 in a Dutch journal⁵ and later in *Nature*⁶. O'Brien⁷ filed a U.S. patent based on his work in 1954.

In the meanwhile, work was also underway in England by H. H. Hopkins et al⁸ on techniques for producing image-carrying fiber bundles with good alignment of the fibers although they apparently had not yet recognized the possibility of optically insulating the fiber by means of a low refractive index coating.

The early work of O'Brien was taken up beginning late in 1954 by the Research Department of American Optical Company in Southbridge, Massachusetts where it still continues. The work begun by H. H. Hopkins in England was continued by his pupil Kapany at the Institute of Optics of the University of Rochester, at Bausch and Lomb Optical Company in Rochester, New York, and later, at the Armour Research Foundation in Chicago, Illinois. Still another group in the U.S. began work on fiber optics during this period, namely, Curtiss et al⁹ at the University of Michigan in Ann Arbor, Michigan. This work was later taken over by American Cystoscope Makers, Inc. of Pelham Manor, New York. By 1958 there were thus at least five groups actively engaged in research and development in fiber optics in the U.S. and the technology advanced rapidly. Curiously enough, during this period, there was practically no fiber optics activity reported from outside the U.S.

During the past four years fiber optics has gradually emerged from the laboratory and evolved into a commercial enterprise. At least six firms in the U.S. are now engaged in the manufacture and sale of fiber optics materials and devices including: American Optical Company, American Cystoscope Makers, Inc., Bausch and Lomb, Inc., Chicago Aerial Industries, Mosaic Fabrications, Inc. (Southbridge, Massachusetts) and Optics Technology, Inc. (Belmont, California). Research and development in various specialized phases of fiber optics is also continuing at a number of institutions in addition to these firms. Products and systems incorporating fiber optics are under development by many firms and laboratories throughout the U.S. and other countries although most of the fiber optics materials are being supplied by the six U.S. firms named above.

Principles of Fiber Optics

Fiber optics is based on two essential principles: 1) smooth filaments or fibers of transparent materials such as glass conduct light with high efficiency by means of total internal reflections along the walls and 2) individual fibers in a cluster or bundle conduct this light independently of one another. In practice, one finds that both these principles apply rather well to coated (i.e. optically insulated) fibers but not very well to uncoated fibers. In the case of coated fibers the first principle makes it possible to obtain useful transmission through fibers of up to several meters in length (the limit being imposed primarily by the absorption of the fiber material) while the second principle makes it possible for a fiber bundle to transmit an image by dissecting it into as many components as there are fibers in the bundle and then reassembling it at another location. Moreover, by using a different fiber arrangement at the two ends of the bundle it is also possible to transform the shape of the image.

Coated Fibers

Efficient conduction of light through fibers is made possible by the almost incredible perfection of the phenomenon of total reflection in the absence of disturbing influences. In principle, the conditions for total reflection exist at any smooth interface between two transparent media having different refractive indices, for example, between glass and air. Thus a smooth glass fiber in air should conduct light efficiently. In practice, however, one finds that the presence of minute defects and contamination at the interface interferes with the total reflection phenomenon by absorbing or scattering away a fraction of the incident light. While not generally important in prisms involving at most a few internal reflections, these losses become serious in fiber optics since each ray may undergo hundreds or thousands of reflections in its passage through the fiber. Thus one usually finds that uncoated, freshly drawn glass fibers rapidly lose their initial transmission efficiency, due to surface contamination.

Even if it were possible to adequately protect uncoated fibers from contamination they still would be unsuitable in many applications due to leakage of light from one fiber to the next. This leakage, sometimes called "optical crosstalk," is due to the penetration of the electromagnetic field into the rarer medium during total internal reflection. The extent of this penetration is only

of the order of the wavelength of light but when another fiber is brought to within this distance some of the light from the original fiber leaks across the interface and the total reflection is said to be "frustrated."

Attempts to prevent this leakage by coating the fibers with a highly reflecting metal such as silver were made by van Heel^{5,6} but the absorption of light by the metal at every internal reflection (several percent per reflection) virtually destroyed the transmission efficiency of the fibers. Only through the use of a transparent dielectric coating was it possible to avoid crosstalk and also maintain high transmission. Initially organic lacquers and ethyl silicate coatings were used with moderate success. Later, still better results were obtained by using a low refractive index glass coating or cladding, as it is often called, over the higher refractive index fiber core. Not only did this produce a fiber with superior optical properties but it also permitted a whole new family of fiber optic devices to be made. For some applications, it also proved desirable to add a second coating which instead of being transparent is strongly absorbent and serves to reduce or eliminate stray light.

Optical Design Considerations in Fibers

Although optical fibers are basically waveguides for electro-magnetic radiation at optical frequencies, many of their properties can be expressed in terms of geometrical optics.

Numerical Aperture:

As in the case of lens optics this is a measure of the light gathering power and is one of the principle properties of a fiber. Figure 1 shows three types of cylindrical fibers: a) uncoated, b) coated and c) double-coated. In each case a meridional ray is shown entering the fiber and reflecting from the innermost interface at the critical angle Φ_c . This angle represents the smallest angle at which the ray can be totally reflected from this interface and thus determines the maximum angle α at which a meridional ray can be accepted for transmission along the fiber. From Snell's law and simple trigonometry one obtains:

$$\sin \alpha = \sqrt{n^2 - 1} \quad \text{Eq. (1)}$$

for an uncoated fiber surrounded by air (or a vacuum) and

$$\sin \alpha = \sqrt{n_1^2 - n_2^2} \quad \text{Eq. (2)}$$

for a coated or double-coated fiber.

If the incident ray is in a medium of refractive index n_o (greater than unity) then these expressions become:

$$n_o \sin \alpha = \sqrt{n^2 - 1} \quad \text{Eq. (3)}$$

$$n_o \sin \alpha = \sqrt{n_1^2 - n_2^2} \quad \text{Eq. (4)}$$

The last expression, Eq. (4), is the most general form and the one usually given. Equation (3) would apply only under very unusual circumstances.

By analogy with lens optics the term $n_o \sin \alpha$ is called the numerical aperture or N.A. of the fiber. Strictly speaking, it applies only to meridional rays and hence it is more appropriate to call this the "nominal" N.A. Skew rays incident at angles larger than α can be conducted by fibers having a perfectly circular cross-section and to some extent by elliptical or regular polygonal cross-sections. Even small departures from perfect geometry, however, cause rapid attenuation of these skew rays so that in effect all the rays are then limited by the nominal N.A.

In practice one finds that the limiting angle α is not as sharply defined as the formula implies, particularly as the size of the fibers is reduced. Diffraction, striae and surface irregularities on the

fiber walls all tend to diffuse the acceptance angle. In general, it is best to assume that the effective N.A. is somewhat less than the nominal N.A. since any rays which are not properly conducted by the fibers must either be absorbed or will appear as stray light and cause image degradation.

The range of nominal numerical apertures available in fiber optics is limited only by the materials from which the fibers can be made. In principle, uncoated fibers of even a quite ordinary glass have a high numerical aperture, but for reasons given earlier such fibers are not usually suitable in fiber optics and will not be discussed further.

For the case of coated fibers, and more specifically glass coated-glass core fibers, one has a fairly wide range of refractive indices from which to choose, thanks to the diligence of the optical glass manufacturers. By selecting various pairs of available glasses it is possible to obtain almost any value of numerical aperture up to about 1.2* and down to as small an amount as desired limited only by the variations in refractive index in the materials themselves.

Unfortunately, not all pairs of glasses can be arbitrarily selected, however, since other factors must be considered such as chemical and thermal compatibility, stability, light attenuation and cost. In some cases the choice of material is also influenced by the fiber drawing process used. For example, it is often desirable for the cladding glass to be in the form of a tube and therefore ordinary commercial grade glass tubing is commonly used for the cladding in place of optical glass. On the other hand, the core glass is nearly always some form of optical glass.

In selecting the type of glass to be used the designer is often confronted with a compromise between numerical aperture and transmittance. In general, the higher the core glass index the higher the N.A. but the lower the transmittance in the blue end of the spectrum. For short fiber applications such as field flatteners or CRT faceplates a high N.A. can be used since transmittance losses will not be serious (except perhaps in the extreme violet and U.V.). For long fiber applications where a reasonably faithful rendition of colors is desired it is usually necessary to settle for a somewhat lower N.A.

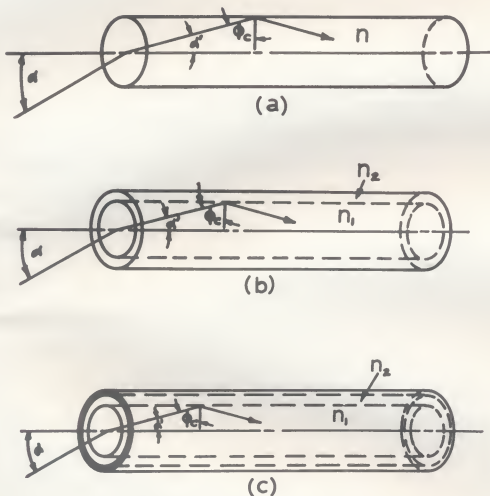


Figure 1: Limiting meridional ray in a fiber
a) Uncoated fiber
b) Single-coated fiber
c) Double-coated fiber

*In the infrared it is possible to go to still high numerical apertures, for example, by employing arsenic trisulfide glass ($n = 2.47$) for the core and a lacquer ($n = 1.50$) for the coating giving a nominal N.A. = 1.96.

Transmittance of Optical Fibers

The transmission of light in optical fibers is governed by a number of factors including: the transmittance properties of the core and coating materials, the quality of the reflecting interface, residual light leakage through the coating and various end losses. To calculate the theoretical transmission of a fiber even with simplifying assumptions as to fiber shape and the geometrical behavior of the rays requires an elaborate integration process¹⁰. A useful simplification is to consider the losses in transmission as consisting of two parts: 1) line losses (attenuation) and 2) end losses.

Line Losses (Attenuation):

The attenuation of light in a fiber is a rather complex phenomenon but for practical purposes may be expressed by the following:

$$I = I_0 e^{-\frac{l}{L(a,\lambda)}} \quad \text{Eq. (5)}$$

where l is the length of the fiber and $L(a,\lambda)$ is defined as the "mean transmission length." This is a function of the angle of incidence, the wavelength and the type of fiber used. When the attenuation is primarily due to absorption by the core glass, and this is usually the case, L varies as $\cos a$. Thus the effective numerical aperture of a fiber changes somewhat with length. The attenuation due to scattering of light by surface imperfections along the core-cladding interface or absorption by the cladding is not as easily taken into account, particularly for small fibers, but it also follows a generally exponential behavior as a function of length. A typical value of L in high transmission fibers is about 4 meters for the green portion of the spectrum.

The transmission of fibers as a function of wavelength, in general, depends primarily on the transmission characteristics of the core glass and secondarily on those of the cladding. Except in very small fibers the light transmitted by the fiber spends most of its time in the core glass and thus is most influenced by the absorption of the core material. For long fibers the core glass must be carefully selected for minimum absorption. Fortunately, there are a number of highly transparent, "water white" optical glasses available with a sufficiently high refractive index to provide a useful numerical aperture. Even with these glasses, however, the transmission is confined largely to the visible and near infrared spectrum,

from about 400 $m\mu$ to 1.7 μ depending, of course, upon the fiber length. Short fibers of regular glass can be used into the near ultraviolet down to about 350 $m\mu$ and into the infrared out to 2.5 μ .

Figure 2 shows two spectral transmittance curves for a fiber core glass commonly used for long optical fibers. Both curves were computed from measurements made on a 100 mm. thick sample of the glass and therefore represent a substantial extrapolation of the measured values. These curves serve to indicate the high potential transmission for fibers made from this material, provided other losses are kept to a minimum. Figure 3 shows similar curves for a higher index core glass (often used for fused fiber bundles). In this case the transmittance in the infrared is even higher than in the previous example but there is also a greater fall-off in the blue.

The line transmittance (i.e. not including end losses) of an actual fiber bundle made from the 1.62 index core glass is shown in Figure 4. This curve is based on data from independent measurements made in the visible spectrum and in the infrared. Although this curve shows the same general characteristics as the solid core glass it also indicates that there are some line losses not accounted for by the absorption of the core glass. Scattering of light at the interface which has been observed may account for part of this. Another possible cause is absorption by the coating glass.

End Losses:

The factors which determine the end losses in fibers include: 1) Fresnel reflection from the entrance and exit faces of the fiber, 2) the packing fraction and 3) the effective numerical aperture. The last of these together with the distribution characteristics of the incident light determines the amount of light which can be accepted. Normally the nominal N.A. is chosen to accept as much of the incident light as possible commensurate with other requirements. The Fresnel reflection losses can be computed from the Fresnel coefficients and may range from about 9% to 17% for both end faces, depending on the refractive index of the core. These losses may be reduced in some cases by means of low reflection coatings.

The packing fraction is the ratio of the cross-sectional area occupied by the fiber cores to the total area. The loss due to this factor may range from a few percent in large fibers to as much as

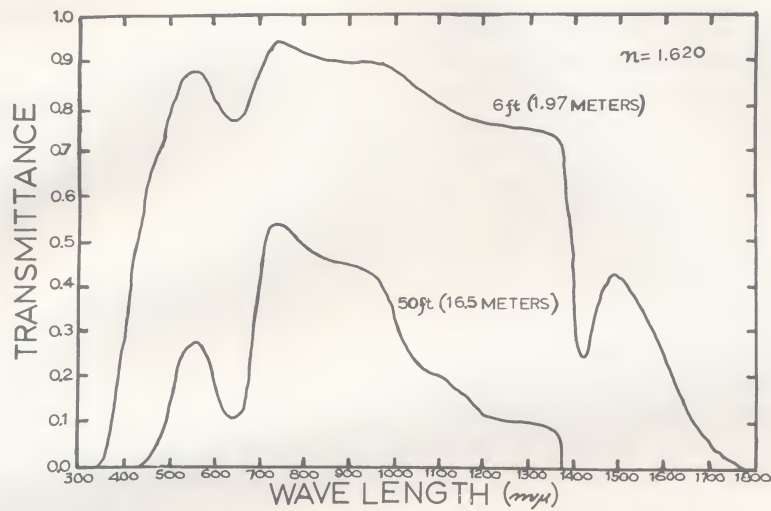


Figure 2: Transmittance curves for a medium refractive index fiber core glass ($n = 1.620$)

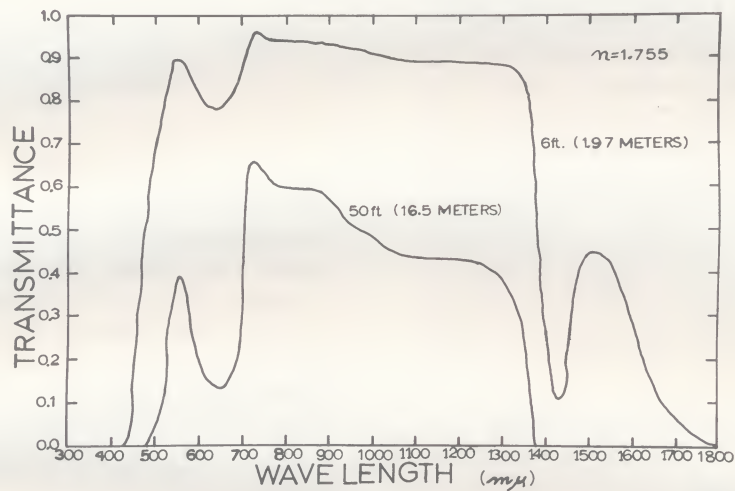


Figure 3: Transmittance curves for a high refractive index fiber core glass ($n = 1.755$)

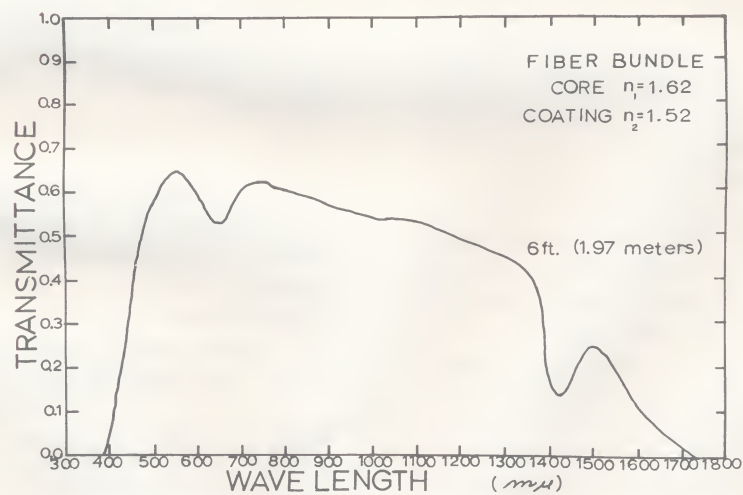


Figure 4: Transmittance curve for a fiber bundle 6 ft. long ($n_1 = 1.62$, $n_2 = 1.52$)

40% for small fibers. Both the fiber coating area and any space between fibers contribute to this loss. Fused fiber bundles are usually more efficient in this regard than cemented bundles since the fusing process eliminates any open spaces between the fibers. The lower limit of this loss factor is set by the fiber size since the coating thickness should be essentially constant for a given fiber shape and numerical aperture. In fibers smaller than about 10 microns this loss factor becomes increasingly serious. For larger fibers it is not a problem in principle, but as a practical matter this loss is usually not less than about 10%.

Infrared Fibers

For wavelengths beyond about 2.5 microns where most optical glasses attenuate rapidly, it is necessary to consider other possible fiber materials. Some work has been done on germanate and calcium aluminate glasses to extend the infrared transmission out to about 5 microns at least in short fiber lengths*. Transmission still further into the infrared has been achieved by using arsenic trisulfide glass. Fibers having a stoichiometric As_2S_3 glass core ($n = 2.47$) and a modified arsenic sulfide coating ($n = 2.416$) have been prepared at American Optical Company, which transmit out to 7 microns for a fiber length of 1/2 meter and out to 12 microns for a length of 7 mm. (Figure 5).

Resolution and Image Quality in Fiber Bundles

Dynamic Resolution:

When an object is viewed through a moving aperture (i.e. by a scanning process) the resolution of the image can be defined in terms of the size of the scanning aperture. This is essentially the same process which takes place when a fiber bundle (or a single fiber, for that matter) is moved laterally relative to the image being transmitted. In this case the fiber core size corresponds to the scanning aperture. In this case, one finds that about 0.8 line pairs per fiber core diameter can be resolved using a high contrast target. In addition, the overall image quality is greatly improved over the static case.

This so called "dynamic resolution" is inadvertently utilized in fiberscopes used for visual scanning whenever the instrument is in motion.

*By Armour Research Foundation under U. S. Air Force Contract No. AF 33(616)6247.

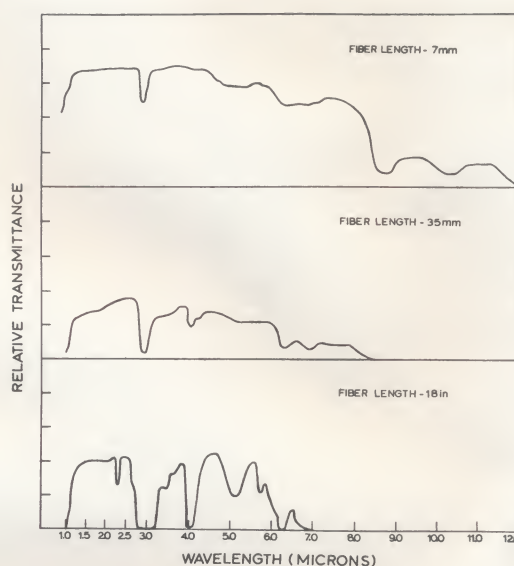


Figure 5: Relative transmittance curves for three different lengths of coated arsenic trisulfide fibers

When the motion ceases or when a photograph is made through the system only static resolution results. A device for achieving continuous "image-compensated" scanning with a fiberscope has recently been developed to permit full utilization of the dynamic resolution of the fiber bundle. In general, any application of fiber optics which incorporates scanning of the image benefits from improved resolution and image quality.

Static Resolution:

Static resolution corresponds to a single sampling with the array of apertures represented by the ends of all the active (unbroken) fibers in the bundle. Due to various kinds of defects which can occur in fiber bundles, static resolution is difficult to define. As a practical matter the static resolution is only about 50-60% of the dynamic resolution† although one may also find significant point-to-point fluctuations. The general image quality for a static system is a function of the number of defective and misaligned fibers and varies considerably with the individual device. As manufacturing processes improve

†Hicks and Kiritsy¹¹ state that the apparent resolving power of static fiber systems for random small figures (as opposed to long edges) is about 1/3 as high as in dynamic system for shape recognition, but 2/3 as high for counting the number of figures.

there should be a steady improvement in the image quality and uniformity of fiber optics devices.

The designer of a fiber optic system must consider the resolution and image quality requirements in specifying the fiber parameters. As a rule, he should not overspecify his resolution requirements since this may adversely affect both the transmission efficiency and possibly the cost of the system. This applies mainly to fiber sizes below 10 microns. Wherever possible, a dynamic system should be considered.

Forms of Fiber Optics

The Single Fiber:

The simplest form of fiber optics is the single fiber. Single fibers can be used to conduct light to or from small areas with high efficiency. In small diameters they act as optical waveguides and can be made to transmit only selected modes of electromagnetic radiation. This form of mode selection is of interest in the field of optical masers¹². In this connection, the ability of a fiber, having a neodymium doped glass core, to amplify light by stimulated emission has recently been demonstrated at the American Optical Company Research Laboratory.

Single fibers can be made of almost any diameter from about 2 microns to 1 mm. or more. At what point a fiber becomes a rod is clearly somewhat arbitrary, however, most flexible fibers fall in the range from 15 to 250 microns in diameter with the majority in the range from 50 to 100 microns. For certain purposes where a small core size is required without the need for a small overall diameter it is customary to increase the cladding thickness to provide an overall diameter of about 50 microns for ease in handling.

Through the use of various combinations of core and cladding materials it is possible to vary the numerical aperture, the transmission, the thermal properties and, to some extent, the mechanical properties of fibers. Numerical apertures in the range of from 0.2 to 1.0 are common although lower and higher values are possible.

Fiber materials can be selected to favor transmission in the near ultraviolet (to a limited extent), the visible, or the infrared portion of the spectrum.

Single fibers can also be made to withstand considerable thermal and mechanical stress through proper choice of materials and drawing techniques.

Fiber Optic Light Guides:

These are bundles of single fibers which are either cemented (usually with an epoxy resin) or fused together at the ends and free to flex in between. Since they are intended only to conduct light no deliberate attempt is made to achieve an identical fiber arrangement at the two ends. Such a bundle, therefore, automatically scrambles any input image, which can sometimes be an advantage in an illuminator system.

Figure 6 shows an assortment of round fiber optic light guides. The fiber size used is typically about 80 microns and the numerical aperture about 0.5. Light guides of almost any length and cross-sectional shape and size can be produced within the limitations of light attenuation and cost.

Multi-fibers:

Single fibers less than about 25 microns in diameter are difficult to handle and align into systematic assemblies. From this point of view, in fact, it would be preferable to work with still larger fibers or even rigid rods, but resolution would suffer. This dilemma is resolved through the use of "multi-fibers," consisting of a number of optically distinct coated fibers fused into a



Figure 6: Fiber optic light guides

single strand or rod. Such a multi-fiber has essentially the same mechanical properties as a single fiber of the same dimensions and will be either flexible or rigid depending on its diameter. Flexible multi-fibers consisting of a square array of 36 fiber elements each 10 microns in diameter are regularly used as the building blocks for flexible fiberscopes at American Optical Company. Figure 7 is a photomicrograph showing the multi-fibers in such a fiberscope. (Each multi-fiber is 60 x 60 microns in cross-section.)

Rigid multi-fibers containing a large number of fiber elements are used in the assembly of fused fiber optic plates (optical mosaics). They can also be used alone to transfer images (i.e. rigid fiberscopes or image conduit) and can be readily bent by heating to conform to any prescribed path (Figure 8).

Image conduit can be made with small fiber elements for high resolution. It is free from distortion, rugged and cheap. It should be used whenever possible in place of a flexible fiberscope.

Flexible Fiberscopes:

These are aligned flexible bundles of single

fibers or multi-fibers fitted with suitable lenses at either end and used to transfer images along flexible paths. Fiber optics is probably best known for this configuration (Figure 9).

The numerical aperture and transmission properties of the fibers (or multi-fibers) used in these bundles are generally the same as in the case of flexible light guides.

Early versions of fiberscopes were made with up to 30,000 single fibers of about 50 microns in diameter and thus provided only limited resolution. More recently, multi-fibers have been used for nearly all fiberscopes made at American Optical Company. The individual fiber element size in these multi-fibers is typically 10 microns so that there are about 10^6 elements per cm^2 . Figure 10 shows a resolution test chart photographed through a 2 meter long fiberscope containing approximately 800,000 fiber elements. In this figure the entire field of the instrument is shown. Figure 11 shows the central portion of the field photographed at 3.5x greater magnification. In both figures the 0-1 target represents approximately 6 line pairs/mm. because the chart was imaged at a reduction ratio of 6:1 onto

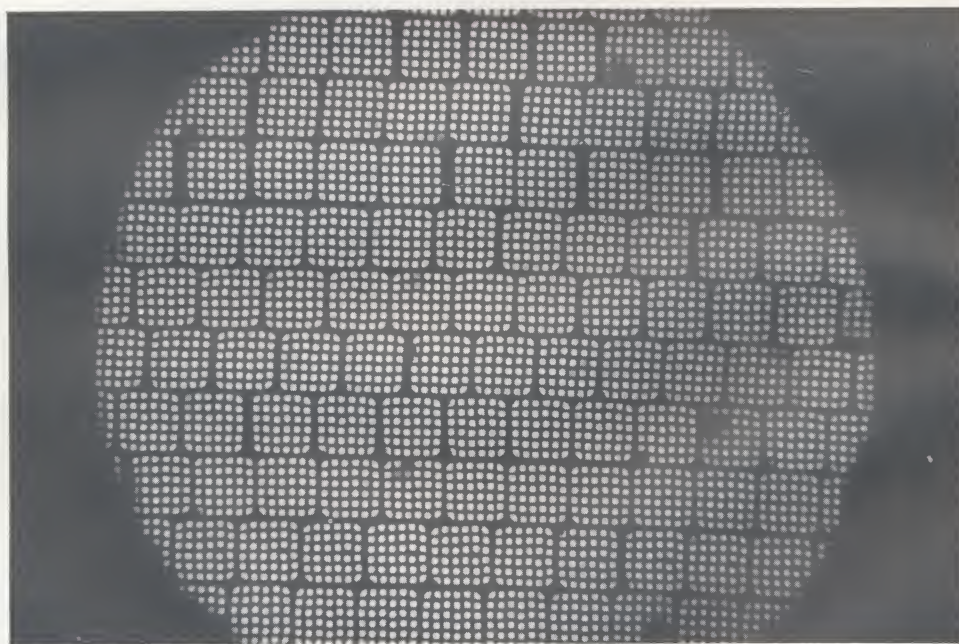


Figure 7: Photomicrograph of a bundle of 36 element multi-fibers (individual fiber element size is 10 microns)



Figure 8: Image conduit containing over 73,000 individual fiber elements



Figure 9: Flexible fiberscope approximately 4 meters long

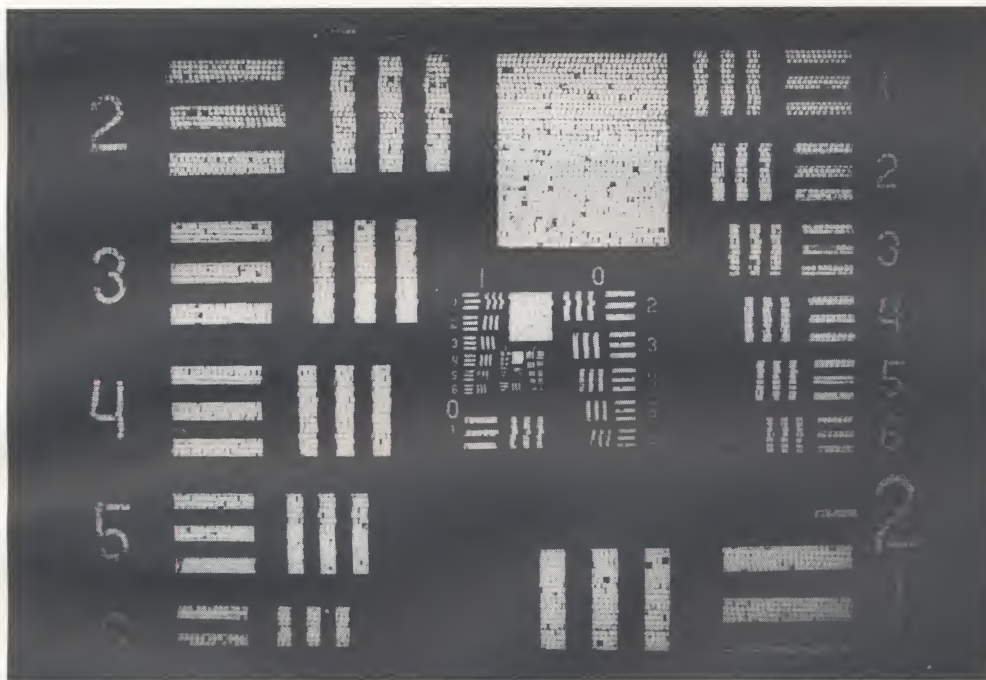


Figure 10: Resolution test pattern photographed through a flexible fiberscope with 10 micron fiber elements

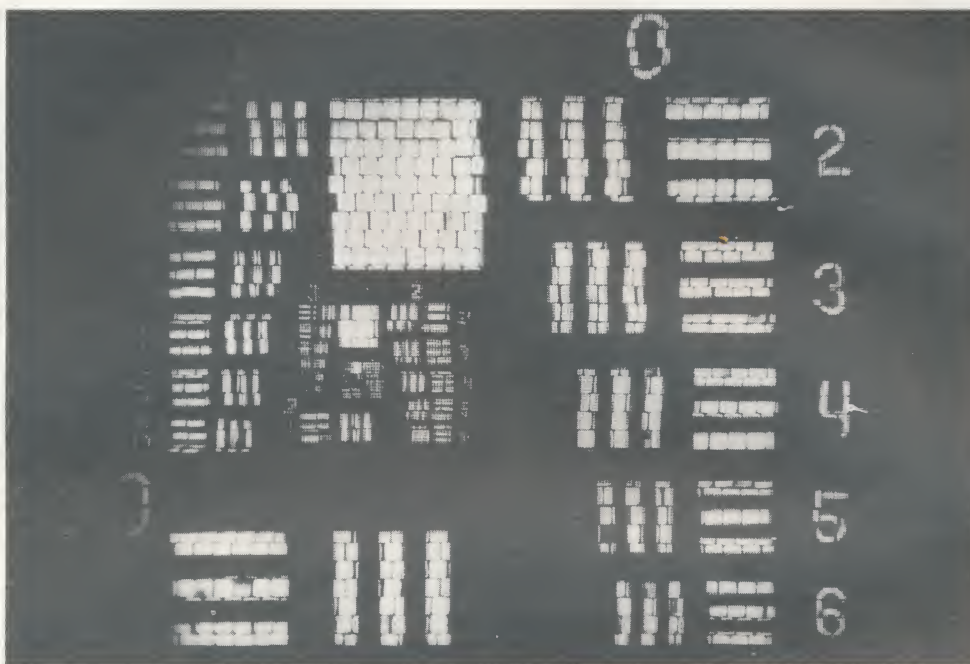


Figure 11: Same as in Figure 10 but magnified 3.5x

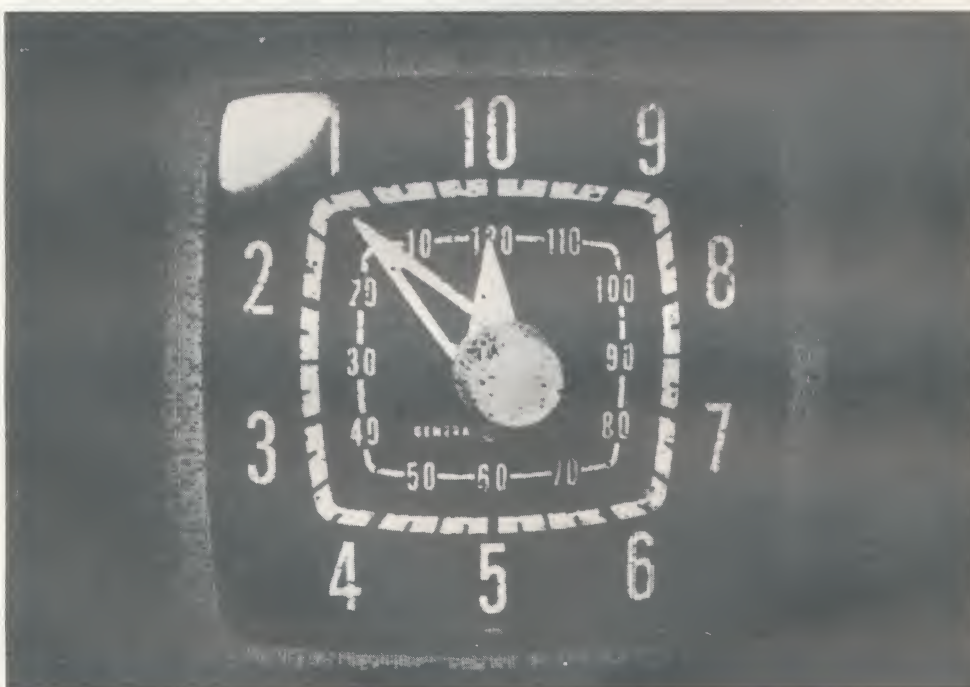


Figure 12: Laboratory timer dial photographed through a flexible fiberscope

the entrance face of the fiberscope by the objective lens. Examination of the original photographs reveals that the 2-4 target is clearly resolved corresponding to about 34 line pairs/mm.

Principal defects are broken or defective fibers and misalignment amounting to as much as 30 microns in some instances. Fiberscopes have been made with as few as 0.2% defective fibers and with somewhat less misalignment than in the example shown, however, it has not yet been possible to completely eliminate all such imperfections. For many applications this overall image quality has proved to be acceptable. Figure 12 illustrates an example of such an application, i.e. viewing a remote dial or other indicator.

Fiberscopes are presently being offered in lengths up to 4 meters but longer ones could be built if needed. One alternative which has been used to provide a greater length is to couple two fiberscopes together but this involves additional losses in transmission and resolution as well as in flexibility.

The largest cross-section regularly available is about 1 cm square and this requires a protective sheath of about 25 mm. in diameter. Larger cross-sections can be supplied but usually at the expense of flexibility.

Fused Fiber Bundles

Single fibers or multi-fibers can be fused together to form a solid block of almost any shape or size capable of transmitting an image from one face to the other. The most common configuration is the fiber optic faceplate used as a tube face for a cathode-ray tube. As in the case of flexible fiberscopes many of the early fused bundles were made with single fibers. Resolution and alignment, however, were rather poor and all fused bundles are now made using multi-fibers of one form or another. This technique has made it possible to systematically assemble large numbers of very small fibers to obtain useful sized faceplates with both high resolution and freedom from distortion.

The principal optical properties to consider in fiber optic faceplates are numerical aperture, resolution and image contrast. Transmittance is generally not a problem except in the ultraviolet. In most faceplate applications where a phosphor is in contact with the fibers a high N.A. is desirable and in some cases, such as in image intensifiers where very low light levels are involved,

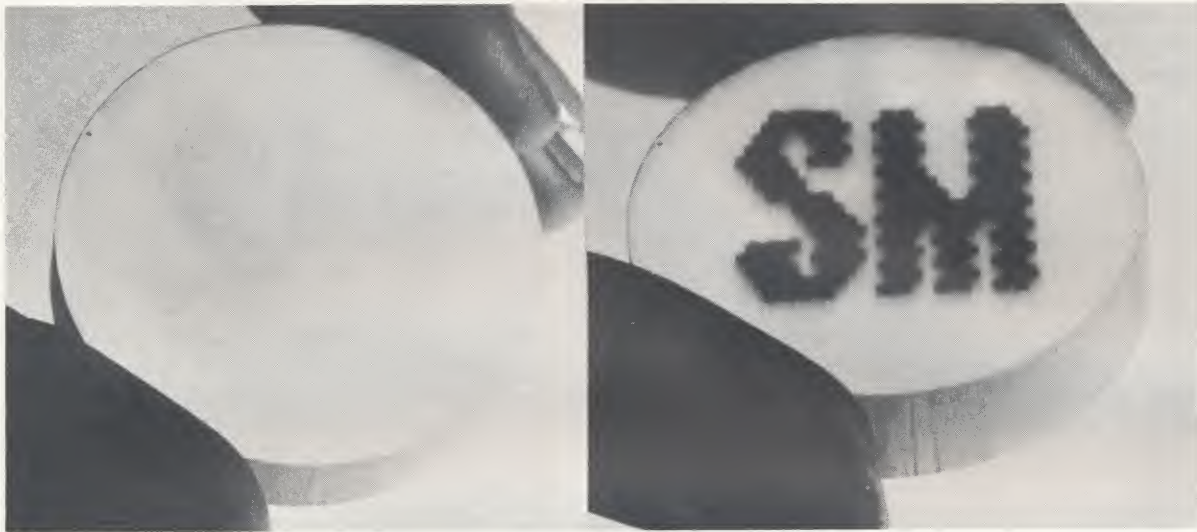
it is essential. Faceplates are available with an N.A. up to 1.0 or slightly higher for maximum light pickup from the phosphor. Where light is not at such a premium a lower N.A. may be adequate and less expensive. In this case, however, the faceplate should be made with double-coated fibers to reduce stray light.

The stray light absorbing property of double-coated fibers is illustrated in Figure 13. This shows two views of a fused fiber optic bundle about 4 cm in diameter and 1 cm thick containing both single-coated and double-coated fibers (both having the same numerical aperture). The double-coated fibers are arranged in a pattern to form the letters "SM." In Figure 13a the bundle is viewed from within the acceptance cone and the "SM" pattern is practically invisible, i.e. the double-coated and single-coated fibers transmit almost equally well. In Figure 13b the bundle is viewed from outside the acceptance cone and the double-coated fibers are now dark while the single-coated fibers continue to transmit stray light (non-image forming light).

The resolution of fused fiber optic faceplates is primarily a function of fiber size but is also influenced by the fiber shape, the numerical aperture and the degree to which stray light is suppressed.

To obtain maximum resolution fiber plates have been made with fibers as small as 3 microns although most "high resolution" plates have a fiber size of about 5-6 microns. Figure 14 is a photomicrograph of a resolution pattern transmitted by a faceplate with 6 micron fibers. The 4-1 target represents 16 line pairs/mm. and on the original photograph the 6-3 target is resolved, corresponding to 80 lines pairs/mm. (or about 60% of the theoretical dynamic resolution based on fiber size).

The shape of the individual fibers in a fused assembly depends on the thermal properties of the core and coating glasses used, on their alignment prior to fusion and on the extent of glass flow required to fill out all the interstices. If the viscosity of the core glass is lower than that of the coating during fusion the initially round fibers take on a polygonal shape. Figure 15 illustrates this condition in an early fused bundle of single fibers. The irregularity of the polygons results from imperfect packing of the fibers prior to fusion. If the core glass is less viscous than the coating during fusion the fiber cores tend to retain their original shape (round, for



a) Viewed at near normal incidence

b) Viewed from outside the acceptance angle of the fibers

Figure 13: Fused fiber bundle containing both single and double-coated fibers

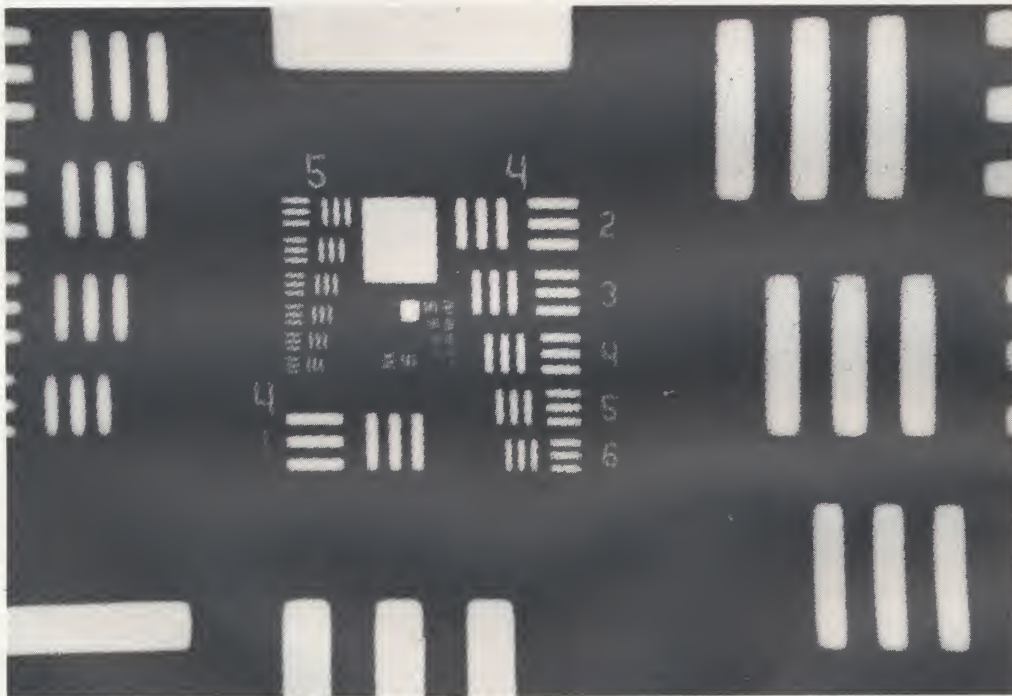


Figure 14: Photomicrograph of a fused fiber bundle placed in contact with a high contrast resolution test pattern (fiber size — 6 microns)

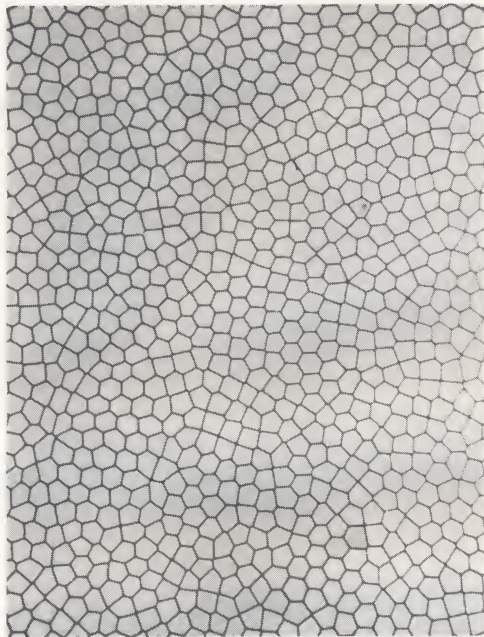


Figure 15: Photomicrograph of a fused bundle of single fibers — core glass of lower viscosity than coating glass during fusion (fiber size — 100 microns)

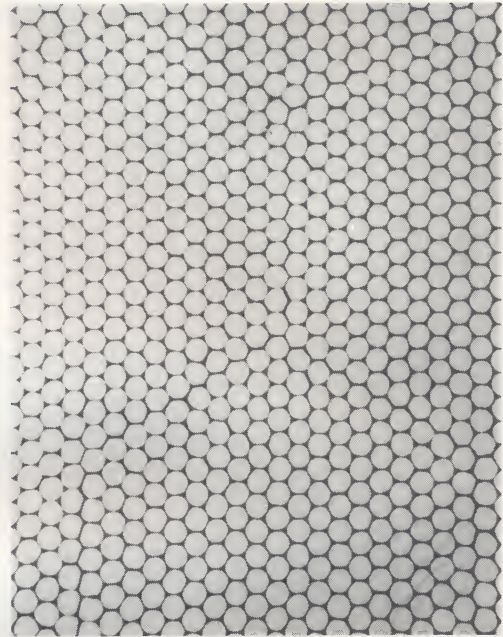


Figure 16: Photomicrograph of a fused bundle of multifibers — core glass of higher viscosity than coating glass during fusion (fiber size — 100 microns)

example) while the coating glass flows into the interstices. Figure 16 shows the fiber shape and pattern for a bundle of well-aligned multi-fibers having a higher viscosity core glass. The individual fibers are about the same size (100 microns) in both cases. Figure 17 shows, however, that these differences in fiber shape and pattern have only a secondary influence on resolution. Figure 17a shows a portion of a resolution pattern photographed through the polygonal fibers and Figure 17b through the round fibers. Only a minor qualitative difference in the information content of the two patterns is discernable.

In addition to the optical properties discussed above there are certain thermal and chemical properties of fiber optic faceplates which are important. In most instances such plates must be vacuum tight and remain so when subjected to the usual bake-out and sealing temperature cycles. Expansion coefficients must be matched to envelope materials to prevent excessive strain or fracture. In some applications such as in image intensifiers the photocathode materials may interact with certain constituents in the fibers. These must either be avoided altogether or isolated by means of an inert coating between the photocathode and the fiber optic plate.

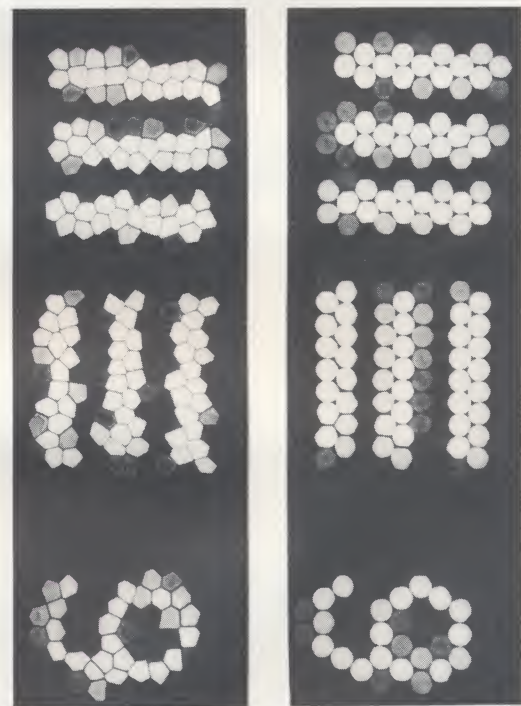


Figure 17: Resolution patterns photographed through
a) the fiber bundle shown in Figure 15 and
b) the fiber bundle shown in Figure 16

In addition to the faceplate configuration described, fused fiber bundles can also be tapered to give image magnification or demagnification. Two such tapered bundles are shown in Figure 18. A specific application for a tapered fiber bundle is described later in this paper.

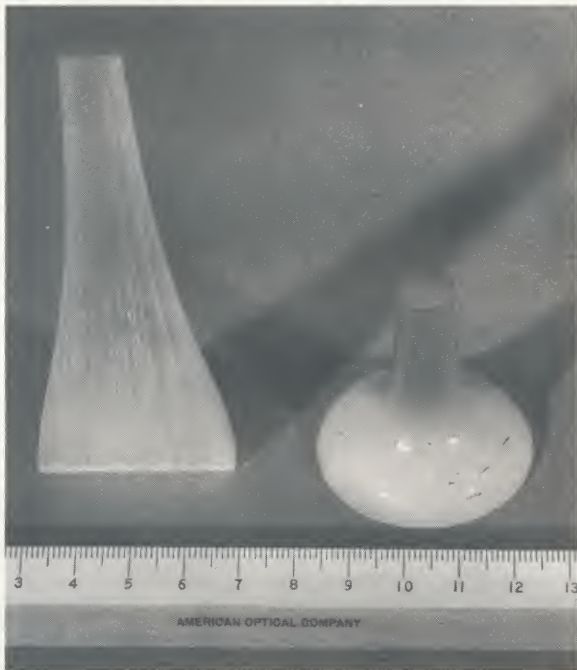


Figure 18: Tapered fiber bundles

Applications of Fiber Optics

There are many potential applications of fiber optics to problems of light and heat sensing. Some of these have already been successfully put into practice while others are still under development. The basic simplicity, flexibility and relatively low attenuation of a fiber optic bundle make it possible to adapt it to a variety of problems in which the radiation must be relayed from the source to the sensor. As was indicated previously useful transmission in the visible spectrum and in the near infrared (out to about 1.3 microns) can be achieved in fiber bundles 50 feet (16.5 meters) long or more. For heat sensing in the infrared spectrum out to 6 microns, bundles of arsenic trisulfide glass fibers of as much as a meter in length can be used.

Fire Detection in Aircraft:

A specific application of radiation sensing in which long fiber bundles are employed is the detection and/or verification of fires in aircraft. In some of the fire hazard areas in aircraft particularly near jet engines the high ambient temperatures make it difficult to install suitable fire detector sensors directly in these areas. Fiber bundles enclosed in rugged shielding have been used to relay the radiation from possible fires in these areas to detectors located up to several feet away behind an insulating barrier. Figure 19 shows a number of such fiber bundles having various lengths designed for use in a U.S. military aircraft.

Present fire detection systems generally involve relaying information by means of electrical signals from the sensors located in the vicinity of

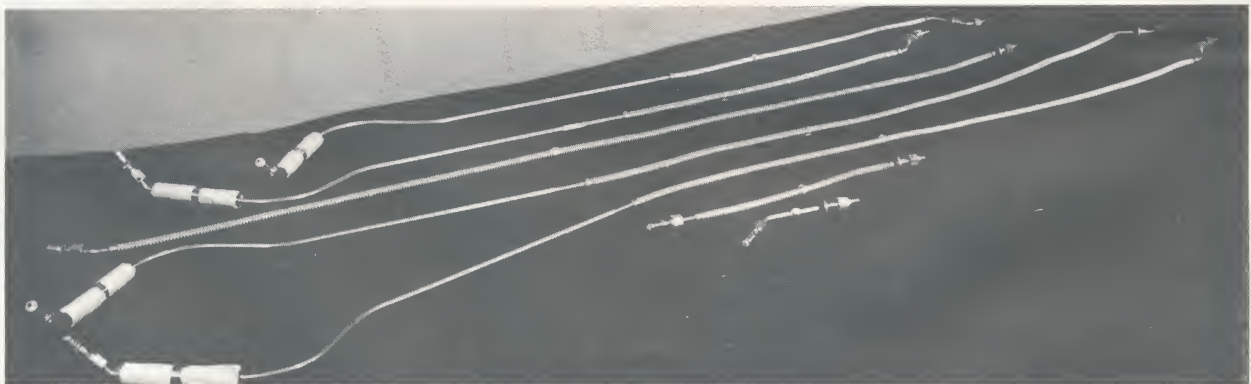


Figure 19: Fiber optic light guides for use in fire detectors in aircraft

hazardous areas to the cockpit of the aircraft. These systems can and often do produce false fire alarms. Without visual verification (i.e. visible smoke or flame) the pilot is confronted with the difficult decision of whether or not to take emergency action. To enable him to obtain visual verification of the existence of a fire it has been proposed that fiber optic bundles be used to monitor the same areas normally under surveillance by the fire detection system.* The exit ends of all these bundles would be brought together at the pilot's (or possibly the flight engineer's) instrument panel where they could be quickly examined when a fire alarm occurs.

One of the principal problems associated with this application is that under certain conditions (such as under reduced pressure at high altitudes) a fire may have a low overall brightness and most of the light may be in the blue portion of the spectrum. Unfortunately, this is the same part of the spectrum which is most strongly attenuated in long fiber bundles. For incandescent type fires, however, having substantial radiation in the green, yellow and red the transmission of the fibers is adequate even in lengths up to 100 feet.

For this application it would be possible to use either image transmitting fiberscopes or fiber optic light guides. The latter would indicate the presence of a fire mainly by the color, brightness and fluctuations in brightness of the transmitted light while the former also could provide additional information regarding the origin and extent of the fire.

Another problem in heat sensing for which the use of fiber optics has been proposed is in infrared scanning or tracking where a flexible bundle of infrared transmitting fibers would be used to couple the seeker optics to a fixed detector which could then be cooled more easily. At the present time coated arsenic trisulfide fibers appear to be the best choice for this application at least in the spectral region between 4 and 7 microns.

Data Recording Application:

Small fiber optic light guides are finding use in a variety of simple optical relay problems where it is necessary to conduct light signals between

the sub-assemblies in an overall system. In such applications they serve essentially the same function as electrical wires. An example of such an application is illustrated in Figures 20, 21 and 22. The instrument†, shown both assembled and removed from its casing in Figure 20, is used to measure the direction and velocity of ocean currents at depths as much as 6,000 meters below the surface. It is a completely self-contained sensing, indicating and recording device which can operate unattended for many months at remote locations in the sea.

The direction and velocity of the current is sensed by a vane and a Savonius rotor supported on jeweled bearings located respectively at the top and bottom of the unit. The motions of these vanes are transmitted into the sealed capsule by means of permanent magnets attached to the vanes. These signals are picked up by other magnets attached to angle coder discs which intercept light from lamps placed close to each disc. These light signals are relayed to the recording camera by means of several small diameter flexible fiber optic light guides. The orientation of the instrument with respect to the earth's magnetic field is determined by a mag-

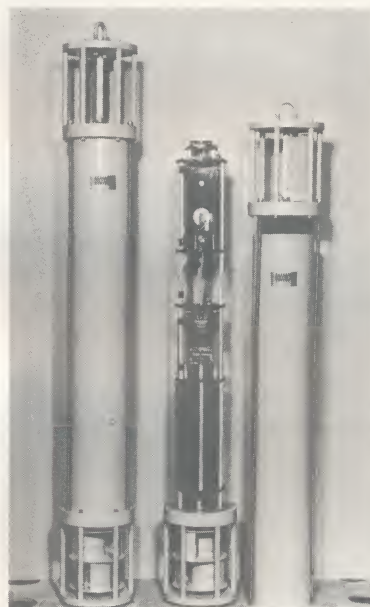


Figure 20: Instrument for recording direction and velocity of ocean currents employing fiber optics light guides (shown assembled on the left and with casing removed on the right)

*This application for fiber optics is currently being investigated by Fenwal, Inc. of Ashland, Massachusetts, under U. S. Air Force Contract AF33(616)-8165. American Optical Company has also participated in this investigation under a subcontract from Fenwal, Inc.

†The Richardson Current Meter manufactured by Geodyne Corporation, Waltham, Mass.

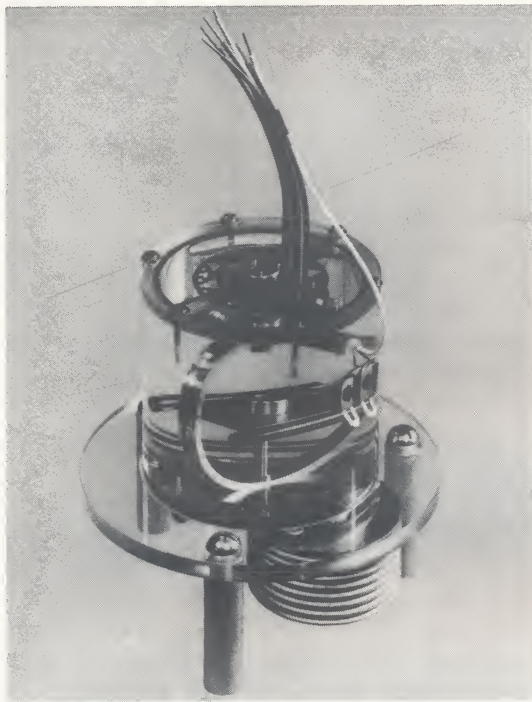


Figure 21: Magnetic compass unit showing use of light guides

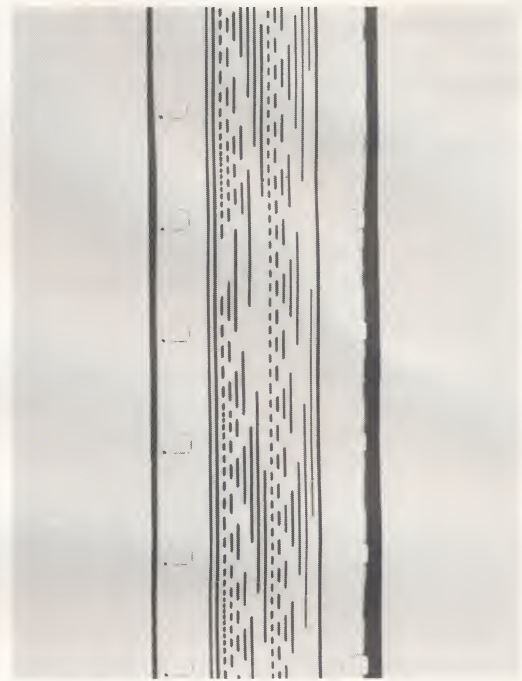


Figure 22: Typical photographic record showing the various information channels

netic compass (also equipped with an angle coder) located at the center of the capsule away from the other sensors. The magnetic compass unit is shown in Figure 21. The angle coder disc and the fiber optic light guides are at the top of the assembly. The light guide shown leaving the side of the unit is used to monitor the lamp output.

The positions of all three angle coders are displayed in terms of light signals on the ends of all the fiber bundles brought together in a single row. An electrically driven camera which can be run either continuously or intermittently records these signals as a series of interrupted lines on a 16 mm. film (Figure 22).

The relatively small amount of power required to operate the camera and the lamps (due, in part, to the high transmission of the fiber optic coupling) permit operating periods approaching the shelf life of the batteries (i.e. up to a year).

Inspection Applications:

One type of problem to which flexible fiber-

scopes have been successfully applied is industrial inspection of hard-to-reach areas. Conventional borescopes have long been used to inspect the insides of tubes and vessels for defects in manufacture and wear. Their use has been limited, however, by the rigidity of the borescope. With the flexible optical system of the fiberscope many new inspection problems can be solved. In the manufacture and maintenance of aircraft or other complex structures it is often necessary or desirable to visually inspect critical areas which are not readily accessible. In many such cases a fiberscope may offer the solution.

Figure 23 shows an example of an industrial type fiberscope suitable for such inspection problems. The flexible sheath (about one meter long) actually contains two fiber bundles, one of which carries the image formed by the objective lens at the forward end of the device to the eyepiece and the other carries light from a small lamp located near the eyepiece to the field of view. A variable transformer supplies the lamp power.

A specific industrial application for such an instrument is illustrated in Figure 24, namely, the inspection of the gasoline level detector in an automobile fuel tank. In this case, the optical system as well as the protective sheath was designed to be used immersed in gasoline. Industrial fiberscopes of up to 4 meters in length have been built for various inspection applications.

Another area of application for fiberscopes is in medical diagnosis. Figure 25 shows such an instrument based on the same principles as the previous example but having a much smaller diameter. (The diameter of this fiberscope is only 3.5 mm.) In this case the light source is located in the box shown on the left which also contains a condensing lens system to concentrate the light onto the end of a small fiber optic light guide which, in turn, transmits it to the distal end of the fiberscope. A 2 mm. diameter objective lens at the distal end forms an image of a 40° field of view on the image-carrying fiber bundle con-

taining approximately 40,000 - 7.5 micron fiber elements. A 25x eyepiece is used to view the image. Although originally developed as a medical endoscope this system can be equally useful in industrial inspection problems requiring a small diameter instrument.

The design considerations in fiberscopes for use in an inspection problem are usually dictated by the specific nature of the problem. In most cases this will directly govern the length, diameter and degree of flexibility required of the system. In some cases it may also require a special design for the distal optics with respect to the field of view, the object distance or possibly a provision for focusing the objective (a remote focusing capability has already been incorporated into some instruments), and the level of illumination whether ambient or provided by the system. In other cases it may be possible to use one of a set of "standardized" fiberscopes such as those shown in Figure 26. These are each about 2 meters long and utilize 10 micron fiber elements.

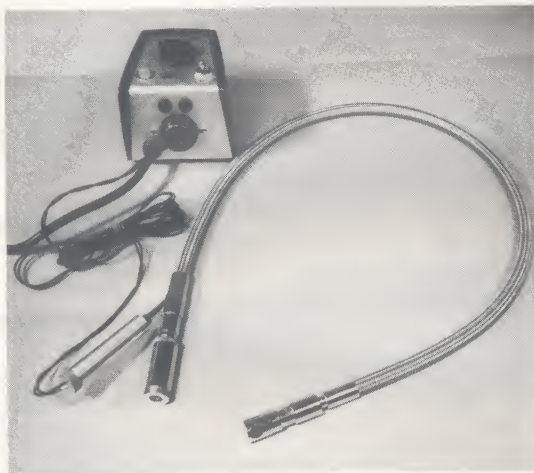


Figure 23: Fiberscope designed for industrial inspection



Figure 24: Fiberscope being used to view inside an automobile fuel tank

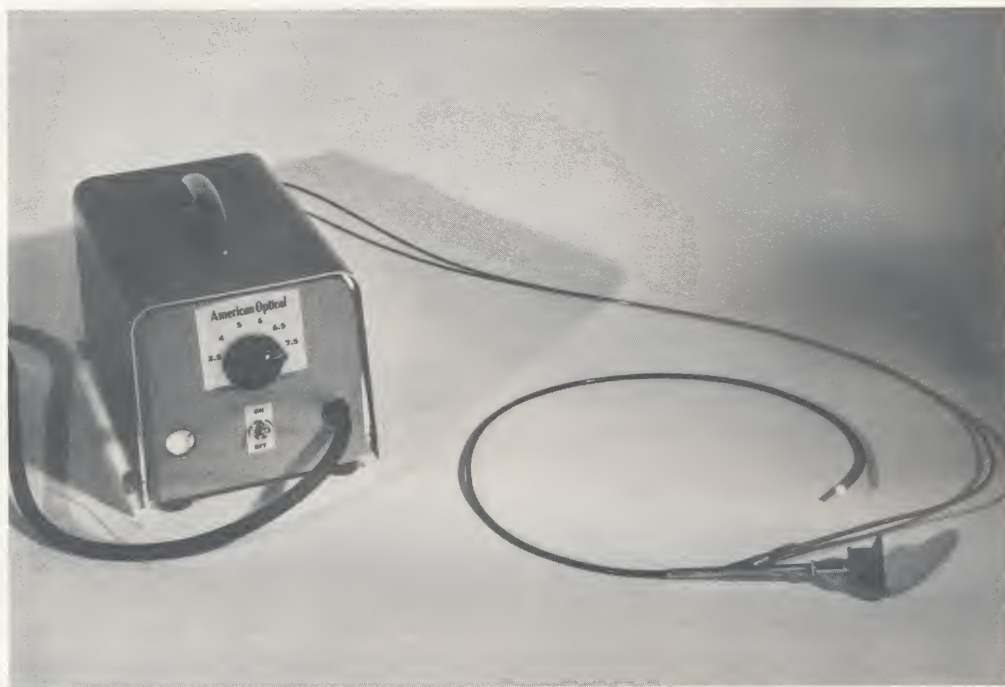


Figure 25: Small diameter fiberscope

Their diameters are approximately 10 mm., 15 mm., and 25 mm., respectively and the two smaller models are fitted with small lamps at their distal ends to illuminate the field of view.

In fiberscopes up to 4 meters in length the transmission losses in the fibers are not generally a serious factor. The image quality, however, depends on the number of fiber elements which is limited by the diameter of the system. Thus it is usually advisable to use the largest fiberscope that will pass into the region to be viewed so as to obtain maximum image quality.

The Viewfinder Application:

Another use of a fiberscope, of direct interest in the field of avionics, is in an optical viewfinder for a photo-reconnaissance aircraft. Because of the severe space problems in a particular high performance reconnaissance aircraft, it was felt that a fiber optic system might be designed which would occupy less space and could be more easily fitted to the existing structure than would a conventional optical relay system.

A fiber bundle built for this purpose is shown in Figure 27. Initially made up of about 1 million (10^6) flexible fibers this bundle was then shaped

to the required contour and potted into a rigid structure using an epoxy resin. The actual length of the fibers in this bundle is 1.3 meters and the individual fiber diameter was 50 microns. The ends of the bundle have an octagonal cross-section, 50 mm. across the width. In terms of the diameter it is the largest fiberscope built so far at American Optical Company. The objective lens and viewing optics were to be supplied by the airframe manufacturer and are not shown. The principal design consideration in this application is the mechanical problem of fitting the system into the limited available space in the aircraft. Neither the length nor the diameter of the fibers requires anything unusual in the way of fiber properties.

One other mechanical consideration in this type of system is the requirement to withstand a variety of environmental stresses including high G-loading, shock, vibration, and the wide range of ambient temperatures and pressures characteristic of aircraft operating environments. Potting the fibers in epoxy resin produces about the most rugged type of fiber optic construction possible and, therefore, was the approach selected for this system.



Figure 26: Industrial fiberscopes of 10 mm., 15 mm., and 25 mm. in diameter and 2 meters in length



Figure 27: Fiberscope for use in an aerial photo-reconnaissance viewfinder



a) without a fiber optic field flattener



b) with a fiber optic field flattener

Figure 28: Photographs made using a curved field lens:

The Field Flattener Application

One of the most difficult aberrations to correct in a high speed photographic objective is the field curvature. By leaving this aberration uncorrected the designer can concentrate his efforts on achieving the best correction of the other aberrations to obtain better image quality or an increase in optical speed or both. A fiber bundle can then be used to flatten the field for photographic purposes.

To demonstrate the effectiveness of a fiber optic field flattener a curved field lens having a relative aperture of $f/1.0$ was fitted with a field flattener with 10 micron fiber elements. Two photographs taken with this lens at $f/1.0$ are shown in Figure 28, a) without the field flattener and b) with the field flattener. Whereas only the central zone is in focus in (a), the entire field is in sharp focus in (b).

The principal design considerations in the fiber optic field flattener are image quality and numerical aperture. Except in the ultra-violet, transmission is not a problem over the range of photographic film sensitivities.

The image quality requirements of the field flattener will generally be dictated by the residual

aberrations of the lens. Ideally the field flattener will not introduce any image aberration except that due to the finite size of the fibers. If this is made smaller than the 25% blur circle of the lens (i.e. the smallest circle containing 25% of the total energy) then the field flattener will not seriously degrade the resolving power of the lens.

Under special circumstances it may be possible to correct the lens distortion by tapering the fibers in a controlled manner during the manufacture of the field flattener.

The numerical aperture of the fibers must be high enough to accept the maximum marginal rays (determined by tracing rays through the lens) even at the edge of the field. This usually means that the numerical aperture of the fibers must exceed that of lens. One way to avoid this is to use a tapered fiber bundle for the field flattener in which the axes of the fibers converge at the center of the exit pupil of the lens. For a lens having an inward curving field, however, this means that the fiber bundle increases the image size with a resulting reduction in image illumination*. In a catadioptric system having a back-

*This can be avoided by a reverse taper leading to an "onion" shaped fiber bundle, a feasible but difficult configuration to manufacture.

ward-curving field a tapered field flattener reduces the image size and increases the image illumination, in effect, increasing the optical speed of the overall system.* In this arrangement the maximum use is made of the intrinsic numerical aperture of the fiber bundle. For example, in the system shown in Figure 29 the numerical aperture of the catadioptric system (consisting of a spherical mirror and two achromatic meniscus corrector lenses) is 0.61, corresponding to $f/0.82$. This is increased to a numerical aperture of 1.0 corresponding to $f/0.5$ by the tapered field flattener providing a nominal increase of 2.7 times in effective optical speed. Transmission losses by the fiber bundle would probably reduce this gain to about 2.2 times.

Cathode Ray Tube Display Application

The use of fiber optics in connection with direct recording from a cathode-ray tube is described in considerable detail in the next paper

*This application of fiber optics is being investigated at American Optical Company under U.S. Air Force contract AF 33(616)-6171.

being presented at this meeting and so will not be treated here. Another possible use for fiber optics in a CRT, however, is in connection with visual display under conditions of high ambient illumination. Ambient light falling on an ordinary CRT is diffusely reflected by the phosphor and reduces the contrast of the display. Under severe conditions the display is washed-out altogether.

By means of a special type of fiber optic faceplate it is possible to substantially reduce the amount of ambient light which can reach the phosphor screen without significantly reducing the brightness of the display over a restricted viewing angle. Such a faceplate consists of fibers having a double coating (the outer one of light absorbing glass) and a relatively low numerical aperture. Any light incident upon the faceplate at angles greater than the acceptance cone of the fibers (i.e. the viewing angle) is absorbed by this outer coating and never reaches the phosphor screen. The lower the numerical aperture of the fibers the narrower the viewing angle and the better the rejection of ambient light. For example,

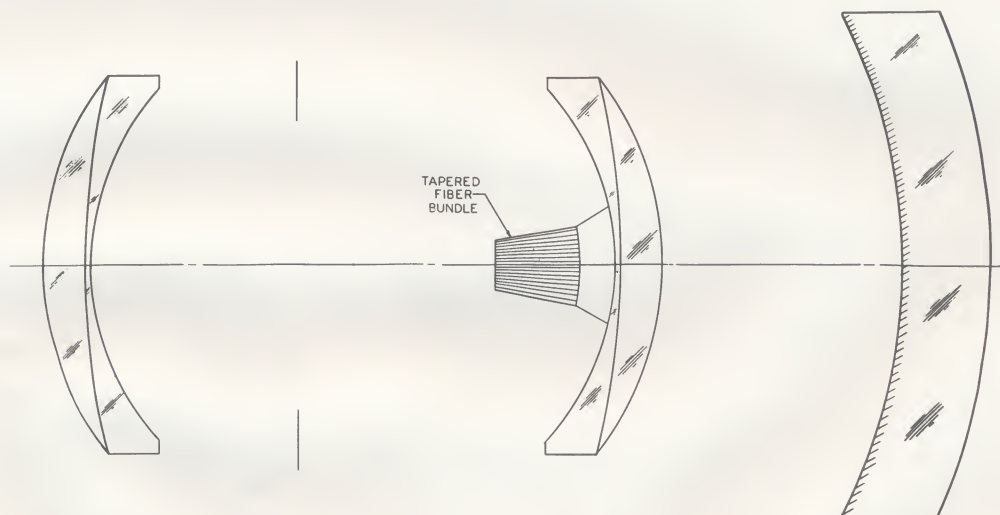


Figure 29: Catadioptric system utilizing a tapered fiber optic field flattener to increase the effective optical speed of the system

A small experimental CRT fitted with a fused fiber optic faceplate consisting of double-coated fibers is shown in Figure 30. The dark central area of the faceplate (3.5 cm in diameter) contains the fibers and the outer ring consists of ordinary clear glass. The P-11 phosphor was deposited both on the fiber optic disc and on the clear glass

ring.

An additional advantage of such a faceplate is the absence of parallax between the image on the phosphor and the face of the tube, thereby permitting more accurate measurements to be made on the image.

Possible uses for this type of faceplate include radar or other CRT displays in an aircraft cockpit (where a hood is a hindrance to the pilot), in control tower operations or in any situation where high ambient illumination is a problem and a restricted viewing angle can be tolerated.



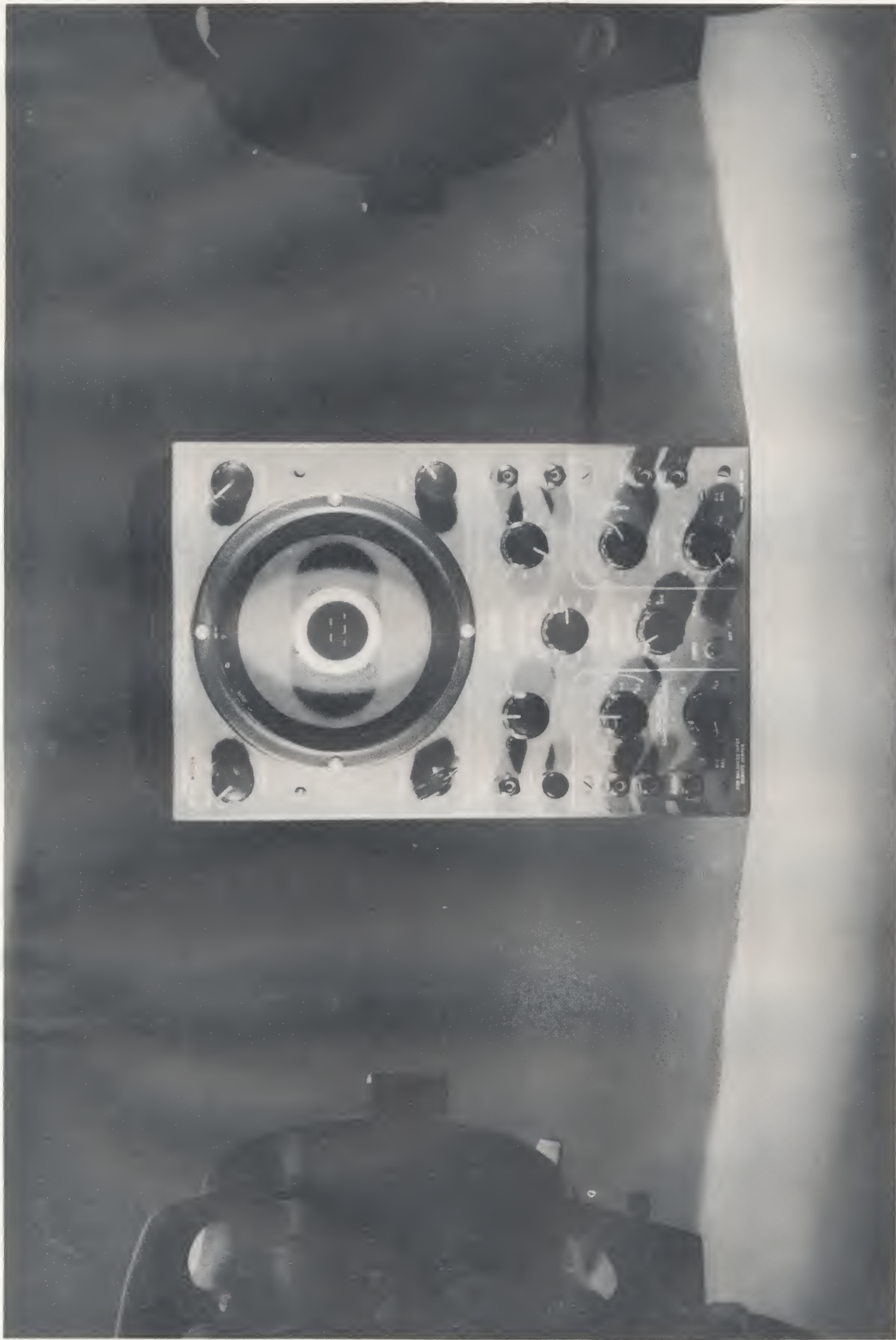


Figure 31: Experimental CRT used in an oscilloscope. The trace on the screen is clearly visible despite the strong side lighting from the two 500 watt lamps

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AMERICAN OPTICAL COMPANY

SPACE-DEFENSE DIVISION

Southbridge, Massachusetts, U.S.A.

FOUNDED IN 1833

THE USE OF FIBER OPTICS IN DATA PROCESSING EQUIPMENT

Designers of data processing equipment use fiber optics and related electro-optical technology to increase the speed, reliability, and versatility of their equipment at a significantly lower cost. Attached are some of the general design considerations and characteristics of fiber optics which American Optical has found most useful to the engineer contemplating the use of fiber optics in data processing applications.

Since pioneering the development of fiber optics into commercially feasible components and assemblies, American Optical Company has continuously worked with engineering groups using this new technology in their specific applications. Experience has indicated that each application has unique requirements of size, configuration, and sensitivity. For this reason, a standard specification covering all potential applications is not feasible. Such standardization would in fact tend to compromise the very flexibility which fiber optics offers the design engineer. Therefore, we suggest that our electro-optical engineers be consulted as early as possible in your developmental cycle in order to take advantage of their skills and past experience.

The material enclosed contains some of the specification values most frequently used in data processing applications. In addition, we are enclosing a basic paper on the characteristics of fiber optics as well as some of our regular data processing sheets to indicate the availability of standard fiber optics components which may be used in prototype work.

Thank you very much for your interest in American Optical's fiber optics program. I look forward to working with you on your future requirements.

Very truly yours
AMERICAN OPTICAL COMPANY

Arthur F. Fiddes

Sales Manager
Fiber Optics

AFFiddes/at1

Enc.

THE JOURNAL OF THE AMERICAN MEDICAL ASSOCIATION

PUBLISHED WEEKLY
CHICAGO, ILL., U.S.A.

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SPECIFICATION PARAMETERS

The commercial availability of flexible bundles of glass fibers, in a variety of sizes and configurations, has greatly accelerated the use of electro-optical systems in equipment where quiet operation, high speed, and the need for the versatility of flexible assemblies to fit around equipment obstructions is desired. Fiber optic components containing glass fibers are being used to transmit the energy from a light source through punched cards and tapes, or to reflect from marked sense cards and further carry the energy to sensors.

Important characteristics which have dictated their use include the transmission efficiency of glass fibers, specifically in the range most sensitive to commercially available sensors, and their thermal compatibility with data processing equipment.

The following is a list of typical specification values used in data processing applications. Trade-offs in length, sizes, thermal endurance, and bending radius are reflected in these nominal values. However, such requirements vary from application to application and, consequently, specification values obtainable would also vary according to these physical requirements.

I. OPTICAL REQUIREMENTS

- | | |
|--|--------------------------|
| 1. Numerical aperture (the measure of the light gathering power of fibers) | .55 Nominal |
| 2. Transmission (must be compatible with sensors and detectors) | See attached graphs |
| 3. Packing Fraction (indicates amount of area actually occupied by transmitting fiber cores) | 75% Nominal |
| 4. Transmittance Uniformity in multiple channel arrays | Between channels
±10% |
| 5. Output light pattern: Round, square, rectangular or other. | |
| 6. Optical Axis: Coincident with mechanical axis within 10° | |

(Over)

II. MECHANICAL SPECIFICATIONS

Mechanical and thermal limitations of fiber optics assemblies are primarily determined by the type of sheathing and/or the type of epoxy or cement used to pot the ends of the fiber bundles. Far greater thermal and mechanical ranges are possible for specific applications. The following represents typical values currently in use by the data processing industry.

A. Endurance or Reliability

1. Flexibility (depends on the type of flexible enclosure at $25^{\circ}\text{C} \pm 3^{\circ}\text{C}$, 80% relative humidity).

Typical values specified are 5000 cycles, of 180° reverse bends to the minimum radius of bend at a maximum rate of one cycle per second with no external longitudinal strain.

2. Vibration (simple harmonic motion, peak acceleration of ten G's, through frequency range of 30 to 2000 hertz within 10 minutes minimum).

3. Bonded Joints: typical push-out strength 500 PSI shear of bonded joint.

4. Crush Resistance (depends on sheathing used).

5. Thermal Shock: typically $+150^{\circ}\text{F}$ to -40°F within 5 seconds.

6. Tensile Load (depends on type of flexible enclosure): Typical value is 5-pound pull.

7. Environmental temperature requirements: Typically -40°F for 48 hours in 150°F for 100 hours at 85% relative humidity.

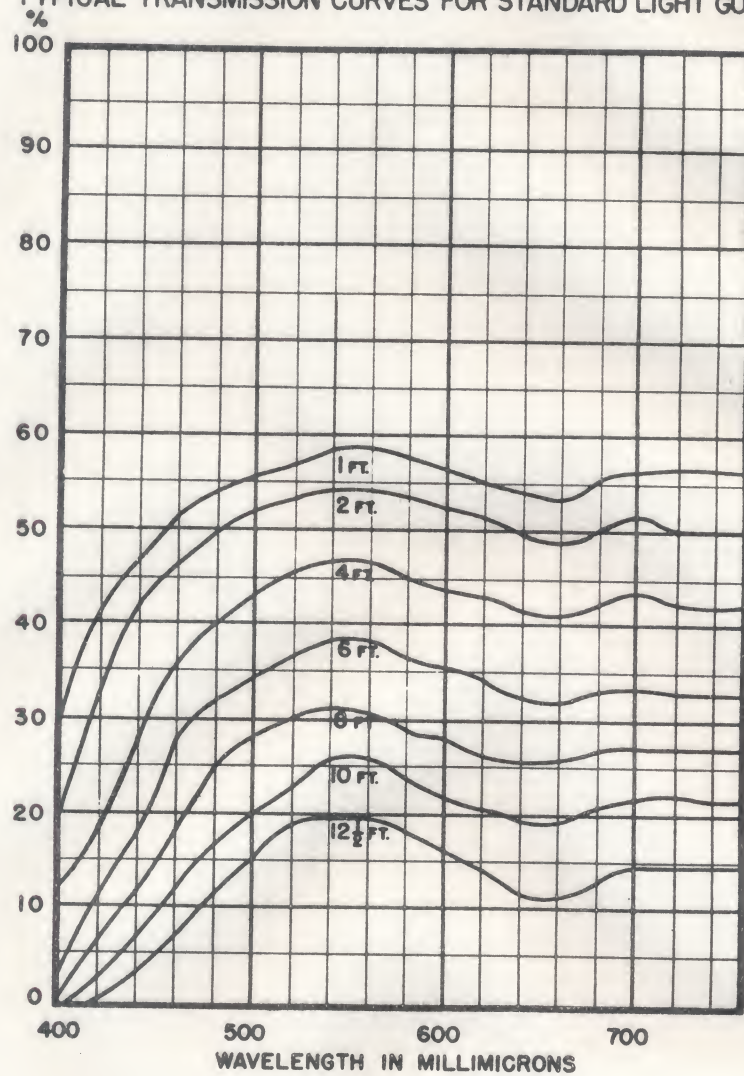
8. Source and Heat Resistivity: Typical 300°F .

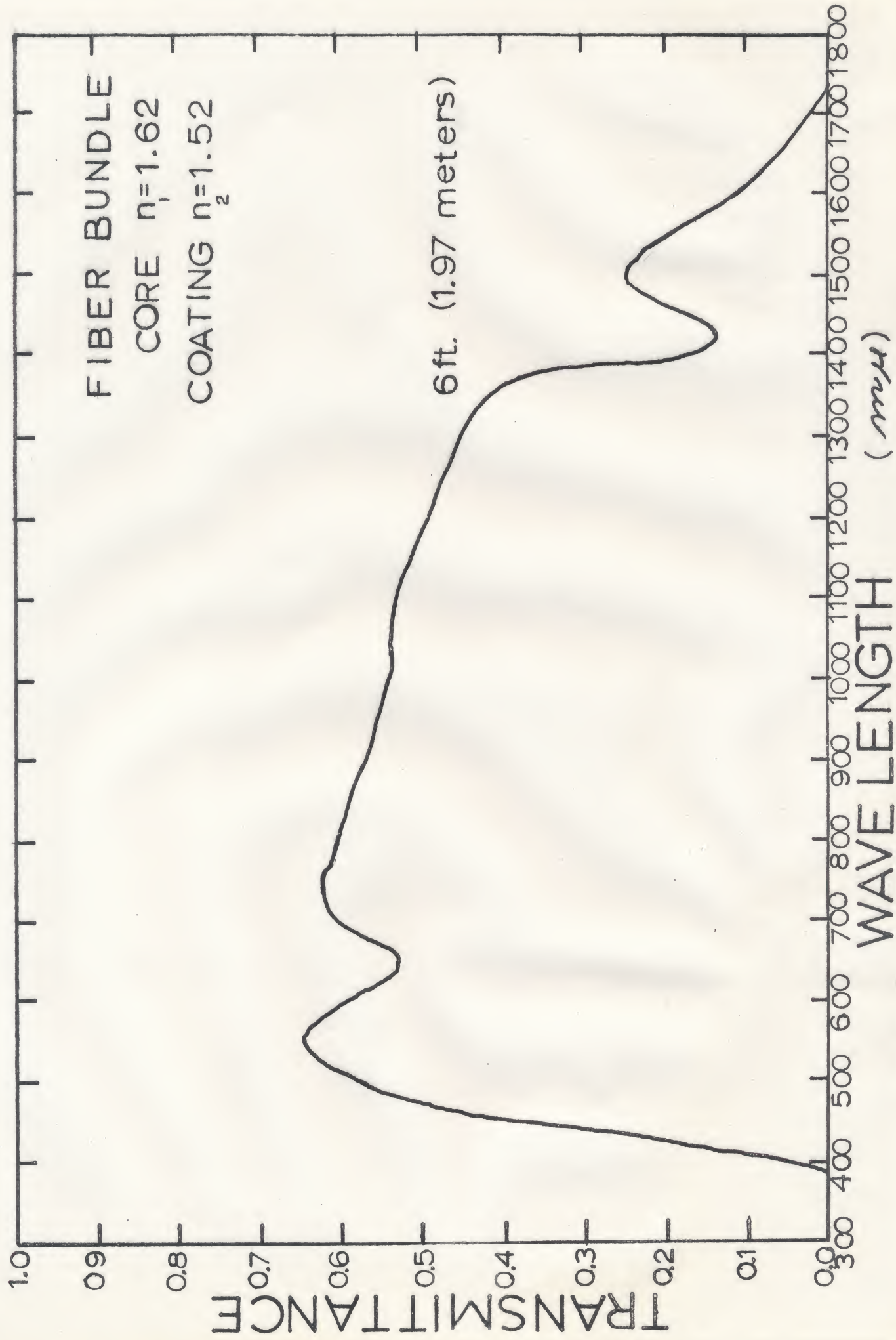
B. Dimensional Tolerances

1. Light Channels: typically $\pm .003"$.

2. Light Channel Location (alignment and positioning): typically $\pm .003"$.

TYPICAL TRANSMISSION CURVES FOR STANDARD LIGHT GUIDES





WAVELENGTH (microns)



TELEVISION OPTICAL SYSTEM

The Fiberscope developed for the Television Optical System has one primary function; to deliver image information from two distinct areas to a single Vidicon Television camera. As well, the system must live in the environmental extremes of the rocket nozzle section of the S-1C booster of the Saturn rocket. The use of a Fiberscope array was dictated by the inability of TV cameras to withstand the high temperatures involved.

Two 6 x 9 mm format, 72 inch-long coherent fiber bundles are used. At the camera end they are joined to provide a 9 x 12 mm format. The objective ends, however, are branched at 180° for the last 48 inches.

The bundles contain 10 micron fibers, and are built using American Optical Company's Multi-Fiber technique. The 10 micron elements yield an inherent resolution of 50 optical line pairs (100 TV lines) per millimeter. All hardware is non-corrosive stainless steel. The system is completely passive -- there are no moving parts and no electrical power requirements.

This system has been qualified to the following environmental extremes:

Pressure:	0.00082 to 14.7 psia
Temperature	0°C to 95°C in two minutes after temperature soak of 30 minutes minimum
Humidity:	100% R. H. at 40°F to 100°F for 24 hours
Fungus:	Non-nutrient to fungus
Vibration:	Sinusoidal 5-2000 cps at up to 0.8 inches D.A. and 20 G's Random: 5-2000 cps at up to 9 db per octave and .5 g ² /cps with overall RMS acceleration of 33 G's

LOX TANK OPTICAL SYSTEM

This system is designed to supply information on the behavior of liquid oxygen in the first stage (S-1C) of the Apollo launch vehicle, while surviving the environmental extremes atop the booster itself.

The system consists of two 9 x 11 nine mm coherent fiber optic bundles, each 108" long. One of these, the Wide Angle Optical System uses a 5.4 mm. F/2, 160° objective lens and is capable of monitoring the entire top surface of the Lox while the tanks are filled to capacity. Visual information is presented to the bundle by the objective lens, and transferred through the fiber optic bundle to a set of relay lenses, and onto film. The camera itself is contained in a pod on the side of the vehicle which is ejected at stage separation. The camera pod and film are picked up by down-range recovery teams.

The second unit, the Narrow Angle Optical System is identical to the first, except for the objective lens; in this case a 10 mm, F/1.8, 60° lens. This system monitors Lox behavior as the fuel is exhausted. Prior to development of these systems, there was no way to acquire the necessary information, since the camera had to be mounted outboard for ejection.

The fiber bundle format, 9 x 11 mm, was chosen to be compatible with standard 16 mm film frame size. They were constructed using American Optical Company's patented multi-fiber technique, allowing the use of image elements 10 microns in diameter. This element size yields an inherent resolution of 50 optical line pairs (100 TV lines) per millimeter. In addition, design consideration for the relay system dictated a curved field. This complication was successfully met by attaching a concave "field flattener" to the proximal end of the fiber optic bundle. This field flattener contained 8 micron fibers, and had the surface facing the relay system ground to a 1.5 inch radius.

This system has been qualified to the Saturn first stage environment:

Pressure: 0.00082 to 14.7 psia applied to the entire optical system

Temperature: -45°C to +65°C

Vibration: (a) Sinusoidal
5-2000 cps at up to 26 G's and up to
0.8 inches D.A.
(b) Random
5-2000 cps at up to 0.3 g²/cps and 9 db/octave,
with overall RMS acceleration of 28 G's

